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STATE OF THE ART SURVEY ON HOLOGRAPHY AND MICROWAVES IN NONDESTRUCTIVE TESTING

Robert C. Grubinskas

Army Materials and Mechanics Research Center
Watertown, Massachusetts

September 1972

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ROBERT C. GRUBINSKAS
MATERIALS MANUFACTURING AND
TESTING TECHNOLOGY DIVISION

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Watertown, Massachusetts 02172

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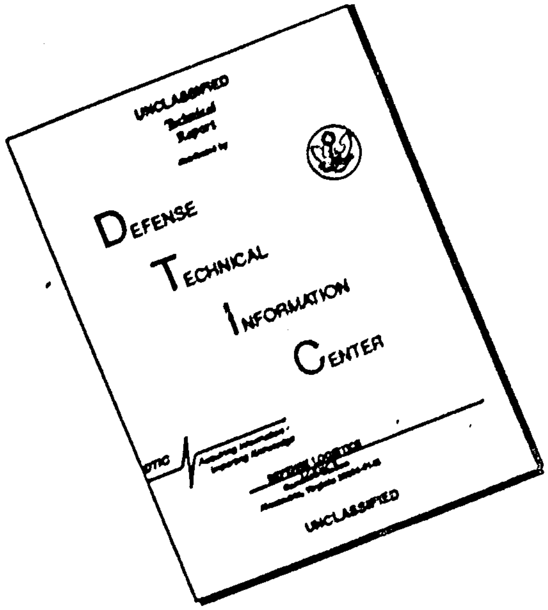

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The object of this monograph is to trace the evolution of relatively new nondestructive testing techniques arising from the vigorously active fields of holography and microwaves. Highlighted areas include the description of existing techniques and a discussion of their capabilities and limitations. Receiving primary emphasis are the applications of these techniques to the evaluation of materials, structures, and end items for quality assurance purposes. An extensive reference and bibliographical section has also been included to increase the usefulness of this document and to provide a launching point for further study. (Author)

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Monograph by

ROBERT C. GRUBINSKAS

September 1972

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MATERIALS MANUFACTURING AND TESTING TECHNOLOGY DIVISION
ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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ABSTRACT

The object of this monograph is to trace the evolution of relatively new nondestructive testing techniques arising from the vigorously active fields of holography and microwaves. Highlighted areas include the description of existing techniques and a discussion of their capabilities and limitations. Receiving primary emphasis are the applications of these techniques to the evaluation of materials, structures, and end items for quality assurance purposes. An extensive reference and bibliographical section has also been included to increase the usefulness of this document and to provide a launching point for further study.

FOREWORD

This report was prepared under a project entitled *State of the Art Survey on Holography and Microwave Technologies in Nondestructive Testing.* This work was performed under the auspices of the U. S. Army Materiel Command's Materials Testing Technology Program, Department of Army Project Number M716350, AMCMS Code Number 4931.OM.6350. This work, which spanned the time interval from October 1970 to March 1972, was conducted with the twofold purpose of (1) contributing to the support of the overall effectiveness of the Army's Quality Assurance Program and (2) providing inputs to the Technical Cooperation Program as undertaken by Sub-Group P on Materials, Working Panel 4, on Evaluation Methods for Materials and Materials in Structures.

The author wishes to acknowledge and to express his gratitude to the following individuals and/or concerns for the provision of illustrative material: To Mr. Paul G. Lingenfelder formerly with the Naval Electronics Laboratory Center, San Diego, California, for the use of Table II, Figures 2, 3, and 10 to 26; to GCO, Inc., Plymouth, Michigan, for the use of Figures 28, 30, 31, 33 to 42, and 50; to Dr. Alexander Hammer, U. S. Army Weapons Command, Research and Engineering Directorate, Rock Island, Illinois, for the use of Figures 29, 44, 48, and 49; to Mr. Harry L. Ceccon, U. S. Department of Transportation, Transportation Systems Center, Cambridge, Massachusetts, for the use of Figure 32; to Dr. Charles M. Vest, University of Michigan, Ann Arbor, Michigan, for the use of Figures 43 and 45 to 47; to Mr. Robert Aprahamian, TRW Systems Group, Redondo Beach, California, for the use of Figures 51 and 52; to Mr. Byron B. Brenden, Holosonics, Inc., Richland, Washington, for the use of Figures 54 to 67; to Miss Theresa M. Lavelle, Frankford Arsenal, Philadelphia, Pennsylvania, for the use of Figures 70 to 76 and 79 to 83; and finally, to Mr. Lester Feinstein, NASA Ames Research Center, Moffett Field, California, for the use of Figures 84 to 87.

CONTENTS

INTRODUCTION

Concurrent literature searches were performed on the subjects of Holographic and Microwave Nondestructive Testing. This work, which spanned the time interval from October 1970 to March 1972, was conducted from the standpoint of assessing the applicability of these technologies toward the evaluation of materials, structures, and end items for quality assurance purposes. The description of existing techniques, their capabilities and limitations, and their adaptation to materials evaluation in both laboratory and industrial environments represent the substance of this monograph.

To supplement the examination of pertinent books and periodicals, literature searches were initiated and performed by the DoD Nondestructive Testing Information Analysis Center, the U. S. Army Foreign Science and Technology Center, The National Technical Information Service, and the NASA Scientific and Technical Information Facility. Additional information was also obtained through personal contacts with researchers and equipment manufacturers.

The work was performed under the auspices of the U. S. Army Materiel Command's Materials Testing Technology Program with the twofold purpose of (1) contributing to the support of the overall effectiveness of the Army's Quality Assurance Program and (2) providing inputs to the Technical Cooperation Program as undertaken by Sub-Group P on Materials, Working Panel 4, on Evaluation Methods for Materials and Materials in Structures.[1,2] These latter inputs, which have been combined and substantially amplified, form the basis of this monograph.

HOLOGRAPHY: GENERAL

Holography is a relatively new method of visualization possessing many unique characteristics of scientific importance. It is a fascinating and rapidly expanding field which is currently undergoing a metamorphosis from the function of being an academic curiosity to the function of assuming a prominent position as an established and widely applied technology. Because of the enormous activity and significant advancements which have been made in holography within the past decade, the following discussion will, of necessity, be very abbreviated and restricted in scope to only those aspects of holography that specifically relate to the nondestructive testing of materials. The extent of this productivity is directly reflected in the number of currently available Holographical Bibliographies and Surveys.[3-15] In addition, several references are available to the reader who may desire to further acquaint himself with the origin and subsequent development of this field from a historical viewpoint.[16-18]

To begin, it would be best, out of considerations of completeness and reader comprehension, to initially discuss what is meant by the term *holography* in a broad sense, and subsequently, in a more comprehensive sense. Generally speaking, holography is basically a technology which deals with a method of storage for use with any type of wave motion – be it electromagnetic in nature such as light waves, or nonelectromagnetic in nature such as acoustical waves – in which both the amplitude and phase of the wave motion can be captured and conveniently released at any later period. Because all of the information about the shape of an object is embodied in the complex wave of radiation which emanates from it

when it is suitably illuminated, the holographic process allows one to record this shape in permanent form in the hologram. Thus, at any later time, the shape can be regenerated and used as a sort of three-dimensional template against which any slight deviations in the geometry of the object can be compared.

More specifically, holography is a method for producing three-dimensional images of coherently illuminated objects by means of wavefront reconstruction and involves the use of highly intense, coherent, and monochromatic waves or beams.* It is a two-step technique, involving the processes of *construction* and *reconstruction* wherein some incident wavefront† is recorded and subsequently reconstructed at a later time independently of its original source. For such a reconstruction to be possible, all of the information about the incident wavefront must be recorded; namely, its *frequency*, *amplitude*, and *phase*. As the frequency in a holographic system is a constant, being specified by the coherent wave source, the problem arises as to how the amplitude and phase information may be recorded simultaneously and all-inclusively. Since most of the existing recording devices are square-law detectors, the amplitude is readily recordable, but the phase is not. The manner in which the phase is rendered recordable is, in actuality, the essence of holography.

For many years since its conception, progress in holography was severely hampered due to the lack of radiation sources possessing the necessary degrees of intensity, monochromaticity, and coherency. With respect to *coherency*, the term is used to describe in a quantitative way the preservation of the uniformity of phase between corresponding points of the wavetrain along and orthogonal to the direction of wave propagation, or, more generally, between two or more points located on either the same or different wavefronts within the wavetrain. These constraints were overcome in large part with the advent of the laser and its eventual application to the holographic process. The degree of the proliferation which has also occurred in the field of laser technology is manifested by the large number of commercially available lasers as is shown in the literature-referenced chart of Figure 1.[19-60] In this figure and the ones to follow, the citation of pertinent literature references will occur at applicable sites within the structure of the chart.

In the construction process, which is illustrated for the optical holographic case in Figure 2, a known and reproducible reference wave is allowed to combine and interfere with an unknown and complex wave, usually referred to as the *signal* or *object* beam, that has been either transmitted through or reflected from some object of interest to produce the incident wavefront. Because both of these waves have been derived from the same source via division of either wavefront or amplitude, they are mutually coherent and combine to produce an interference fringe field corresponding to the sum of their complex amplitudes. The terms *division of amplitude* and *division of wavefront* are used to designate the manner in which two beams may be derived from a single source. In the division of

*The terms *waves* and *beams* are synonymous and will, hereafter, be used interchangeably throughout this monograph.

†It should be noted that in holographic parlance, the term *wavefront* is used to denote the instantaneous state of the two interfering beams on some two-dimensional surface such as a recording medium. This usage is in contrast to the conventional context where the term *wavefront* is used to signify a uniphase surface.

amplitude method (illustrated in Figure 1), the entire cross section of the beam is intercepted by a suitable optical component such as a beam-splitting reflector to produce two outgoing beams from one incoming beam by means of partial reflection and transmission. In the division of wavefront method, only a fraction of the beam cross section is intercepted by a suitable optical component, such as a prism, to produce a phase shift or slight change in direction of only that portion of the intercepted beam while the remainder of the beam continues undeviated along the direction of beam propagation. (The division of wavefront method is illustrated in slightly modified form in Figure 17, where the modification consists of transmitting the hitherto undeviated portion of the beam through a two-dimensional object such as a photographic transparency.)

In the fringe field produced by the interaction of the signal and reference beams, the fringe spacing is modulated or varied by the phase differences existing between the two waves. Therefore, the interference pattern embodying this fringe field is essentially a phase-modulated amplitude distribution whose square can then be recorded by a conventional square-law detector, such as a photographic emulsion placed within the region of interference. The recording is called a *hologram*. The angle between the signal and reference beams, labeled θ in Figure 2, is usually referred to as the *shear angle*. The magnitude of the shear angle and the wavelength of the light used, in turn, determine the orientation and spacing of the fringes comprising the recorded interference pattern. The angle ϕ between the reference beam and the photographic plate is an additional parameter, which, in combination with the other two, influences the resolution requirements of the recording medium.

In the reconstruction process, which is illustrated in Figure 3, the hologram is used as a diffraction grating. When it is illuminated with the reference beam, three beams emerge — a zero order or undeflected beam and two first-order diffracted beams. The diffracted beams produce the real and virtual images of the object to complete the holographic process. In Figure 3, only the first-order diffracted beam which yields the virtual image has been shown, the other two beams having been omitted from the figure for the sake of clarity. If the original object is three-dimensional, then the virtual image is a genuine three-dimensional replica of the object possessing both parallax and depth of focus. The real image, on the other hand, is pseudoscopic or depth-inverted in appearance. Hence, the virtual image — also referred to as the *true*, *primary*, or *nonpseudoscopic* image — is the one which is of primary interest in practical applications of holography.

Although optical holographic techniques have been the most extensively used to date, holography need not be limited to visible light. Here lies the key to the great potential of this technique for nondestructive testing. Holography can, in principle, be performed with any wave radiation encompassed within the entire electromagnetic spectrum; with particulate radiation, such as neutrons and electrons which possess wave-equivalent properties; and finally, with non-electromagnetic radiation such as acoustical waves. The present and future holographic techniques applicable to nondestructive testing are indicated in Figure 4. As can be seen from the figure, the only techniques presently available for practical exploitation are those of optical, acoustical, and electron holography.

Since the interference pattern produced by the interaction of a beam scattered from the object of interest and the coherent reference beam must be faithfully replicated during the construction process, the selection of a suitable holographic recording material for a particular application is of utmost importance. For optical holography, the diverse spatial variations in light intensity constituting the interference pattern are recorded indirectly through the corresponding changes in the physical properties of the material comprising the recording medium. In order to be effectual, the affected physical properties must be capable of interacting with the reconstruction beam, in the second step of the holographic process, to produce the desired image of the object. In general, the interference patterns are usually preserved on or within the recording medium in the form of either an *optical density* or *phase-shift* pattern. In the optical density pattern, the recording material is classified as being *absorptive*, and the stored interference pattern, the hologram, behaves as a density grating which diffracts light by modulating the intensity of the incident reference beam. In the phase-shift pattern, the recording material is classified as being *nonabsorptive*, *phase-only*, or more commonly as just *phase*. Unlike absorptive materials, holograms formed using phase materials possess uniform optical densities and behave as phase gratings which diffract light by means of phase shifts produced by localized variations in the thickness and/or refractive index of the recording medium. In many actual cases, both amplitude and phase variations are present in the same hologram.

Some of the conventional and unconventional materials which have been used for holographic recording purposes are depicted in Figure 5. As can be seen from the figure, these materials divide into the two major categories of absorptive and phase. It should be noted that photographic emulsions, the most commonly used materials, which are basically absorptive can be transformed into phase materials through suitable bleaching and processing techniques. For most of these materials, the recording process is permanent and irreversible. In contrast, certain other materials, such as the photochromics and electro-optic crystals, are erasable, and hence are reusable. Holograms can be further classified according to type, as shown in Figure 6, as being initially either *plane/single-layer/thin* or as *volume/thick;* secondarily, as being either *absorptive* or *phase;* and thirdly, as being either *transmissive* or *reflective*. Generally speaking, the terms plane, single-layer, or thin are used to designate those holograms wherein the interference pattern is recorded as a two-dimensional spatial grating on the surface of the recording medium or in a medium whose thickness is small as compared to the wavelength of the wave radiation being used to create it. Included in the thin hologram category is the *surface relief* hologram where the fringes comprising the interference field are recorded as surface deformations of the recording material. Likewise, the terms volume or thick are used to designate those holograms wherein the interference pattern is recorded as a three-dimensional spatial grating within the volume of the recording medium whose thickness is many times greater than the wavelength of the illumination source. The resultant volume hologram is composed of planes of varying density or index of refraction. Maximum diffraction efficiency is achieved during the reconstruction process when the Bragg condition for reflection is satisfied for discrete values of reference beam angles of incidence and layer spacing. Additional detailed information concerning holographic recording materials and hologram classifications can be found in the literature references cited in Figures 5 and 6.

Another important consideration in the holographic recording process is the resolution requirement which must be met by the recording medium. The equation describing this requirement appears at the top of Figure 7 which also contains plots of spatial frequency versus shear angle for the plane-wave fringe approximation. The term *plane-wave fringe approximation* is used in reference to the interference pattern produced by the interaction of two mutually coherent planar beams. The resulting fringe pattern and its associated nomenclature is geometrically depicted at the lower right-hand corner of the figure. As can be seen by referring to the equation in the figure, the required resolution is a function of wavelength (λ), shear angle (θ), and the angle between the reference beam and the photographic plate (ϕ). These same parameters also determine the orientation of the fringes within the recording medium. For the plots in Figure 7, the bisector of the shear angle is assumed to be colinear with the normal to the plane of the recording medium ($\theta/2 + \phi = 90°$), or equivalently, that the angle of incidence of the object beam is equal to the angle of incidence of the reference beam. Under these conditions, the rectangular-like fringes are oriented parallel to the bisector of the shear angle. Curves A and B bracket the visible light band which contains the curves associated with the output wavelengths of those lasers which have been most commonly used for nondestructive testing applications. The visible light band is also included in Figure 8 with the fringe spacing (reciprocal of the spatial frequency) being plotted as a function of shear angle for the same set of boundary conditions. If spherical waves are used as is often the case in holography, the spacing and orientation will vary across the recording medium with the complexity of these variations increasing with the complexity of the interfering waves.

As photographic emulsions have proven to be the most conventional holographic recording medium used in nondestructive testing applications, a table exhibiting some of the more important holographic characteristics of the most commonly used photographic emulsions is included in Table I. The data for this table was obtained from manufacturer's specifications and the literature (see References 17, 74-80, 108, 169-178). It should be noted that the resolution or resolving power figures encountered in the literature will vary in accordance with the method used to perform the measurement; i.e., by either the customary interference method or by the holographic interferometric method. The results obtained with the latter method are approximately two and one-half times as large as those obtained using classical methods. In addition, these photographic emulsions are sensitized with respect to wavelength so as to yield optimum results when used in conjunction with a particular laser's monochromatic output. For those applications requiring the maximum in resolution capability, photographic emulsions are deposited on optically-flat glass substrates. In less stringent applications, the photographic emulsion may be deposited on a film substrate of either sheet or roll format.

A major prerequisite in the holographic recording process which must be met, if the recording is to be made at all, is that the fringe pattern remain stationary during the exposure period. It should be recalled at this point that interference will occur between any two beams regardless of whether they are derived from either coherent or incoherent sources. When interference does occur with incoherent light, the resulting interference pattern will change rapidly with respect to time because of the randomly changing phase relationships existing between the two interfering beams. Such wavefronts are impossible to record.

With interference occurring between two mutually coherent beams, on the other hand, the successive wavefronts (used here in the conventional sense) in a coherent beam will be identical, and the phase relationships between corresponding points in the two interfering beams will remain fixed so as to produce a stationary interference pattern which is readily recordable. To fulfill the requirement for fringe stability in the recording process, it is necessary to impose controls on the environment in which the recording is to be made. A table denoting *rule-of-thumb* tolerances for some of the most significant environmental variables is included in Table II. Changes in the optical path length or movement of the film, for example, produce fringe shifts. Optical path length changes, in turn, can be produced by localized variations in density, temperature, pressure, and physical movement or vibration of the optical bench and/or optical elements. The actual tolerances listed in Table II are only representative as the actual tolerances are dependent upon the particular circumstances of a given application. Each of the tolerances has been calculated with the assumption that all of the other tolerances are zero. If several quantities do vary simultaneously, then the tolerance on each is smaller than that listed in the table. Also it should be noted that these tolerance values are more relevant to those applications involving continuous-wave lasers as many of these requirements may be substantially relaxed in those applications involving pulsed lasers. A series of optical reference books which may be of use to the reader requiring additional optical knowledge are included as References 179 to 198.

OPTICAL HOLOGRAPHY

The specific geometric methods for hologram generation are delineated in Figure 9. Generally speaking, there are only two distinct types of holograms — the *Fresnel* hologram and the *Fraunhofer* hologram. In Fresnel holography, the object beam represents the Fresnel or *near field* diffraction pattern of the object when it impinges on the recording medium. Similarly, in Fraunhofer holography, the object beam now represents the Fraunhofer or *far field* diffraction pattern of the object when it impinges on the recording medium. All other holograms are special cases of either one of these two categories. Since the differences between holograms and their special properties originate from differences in the construction and/or reconstruction processes, the geometrical diagrams associated with the hologram designations are an important part of their description and have been included herein for the purpose of illustrating the basic differences in geometry of these specific methods for hologram generation. The symbols for the relevant components comprising these geometrical diagrams are included in Figure 10. The geometrical diagrams which depict both the construction and reconstruction processes are grouped in Figures 11 to 23. No further attempt will be made here to describe these specific methods in more detail. Instead, the reader can refer to the literature references which have been provided, with one exception, for all of the remaining elements shown in Figure 9. In addition, suitably referenced geometrical diagrams describing methods for hologram copying; for constructing holograms capable of reconstructing nonpseudoscopic real images of a given object; and finally, for the reconstruction of true images are included in Figures 24 to 26.

When optical holography is applied to materials evaluation problems, the generation of a three-dimensional image of the object, per se, is of little value.

Furthermore, for opaque materials, optical holography is strictly limited to surface observations. Hence, if this technique is to be used for nondestructive testing purposes, supplementary means have to be employed to either stress or impart energy into the test object so as to faithfully produce surface manifestations of the parameter of interest. It is at this juncture that the technique of holographic interferometry plays a significant role.

As in the conventional optical case, holographic interferometric measurements can be made with great accuracy, i.e., to within a fraction of the wavelength of the light being used. Whereas conventional interferometry is usually restricted to the examination of objects possessing highly polished surfaces and simple shapes, holographic interferometry is not. It can be used to examine three-dimensional surfaces of arbitrary shape and surface conditions. Additional points of contrast are as follows. Conventional interferometry must be performed in real time; requires a critical alignment of optical components; and yields a two-dimensional fringe-field readout. Holographic interferometry, on the other hand, can be performed in either real time or at two different times; does not require precise alignment of optical components (except for real-time applications); and yields a three-dimensional fringe-field readout. Because of the three-dimensionality of the hologram reconstruction, a complex object can be interferometrically examined from many different perspectives, wherein the angle of view is limited by only the physical size of the hologram. Thus, a single hologram reconstruction is equivalent to a multiplicity of conventional interferometric observations.

The techniques of holographic interferometry, which are depicted in Figure 27, can be reduced to two basic categories: time lapse and real time. In the time-lapse approach, advantage is made of the fact that more than one hologram may be made on the same recording medium. Examples of this approach include:

Double Exposure or Differential Technique involves the recording of two holograms — one of the object in its natural or undisturbed state, and the other of the object in some changed or disturbed state. In the reconstruction process, the two recorded object beams interfere with one another to produce a fringe field wherein the contour and spacing describe the changes that occurred between the two exposures.

Multiple Exposure or Stroboscopic Technique involves the multiple recording of certain predetermined positions of an object in periodic motion, usually at the positive and negative amplitudes of vibration. In the reconstruction process, fringes of high contrast are produced that enable the measurement of high amplitudes of vibration. By appropriately timing the light pulses, the phase relationships of the antinodes may also be obtained.

Continuous Exposure or Time-Average Technique is an extension of the double and multiple exposure methods to the limiting case involving the recording of a continuum or infinite number of exposures of an object in periodic motion. Because the holographic exposure time is usually much greater than the period of object motion, the hologram is a record of the time-averaged irradiance distribution at the hologram plane. In the reconstruction process, an infinite number of images, corresponding to the previously recorded infinite number of object positions, are produced and interfere with one another. In the resulting fringe

field, the bright fringes correspond to nodal regions (i.e., regions of zero or very small amplitudes of vibration) and dark fringes to antinodal regions (i.e., regions of large amplitudes of vibration). By employing appropriate fringe analysis techniques, the amplitudes of vibration for each point on the object's surface may be determined. Because the fringe contrast decreases as the amplitude of motion increases, the displacement amplitudes amenable to analysis by this method cannot be too great.

In the real-time approach, a hologram is first made of the object in its natural or undisturbed state. The hologram is then reconstructed and precisely repositioned so that the virtual image is exactly superimposed upon the object. Thereupon, the object is disturbed in either a static or dynamic manner. With the hologram being used as an observation window, it is possible to observe the resulting interference pattern produced by the interaction of the recorded object beam (also referred to as the *stored* or *frozen* beam) with a modified, real-time object beam (sometimes referred to as the *live* beam). With this method, it is possible to observe differential, stroboscopic, and time-averaged fields. For time-varying fringe fields, the time averaging is performed by the observer's eye.

Holographic interferometry has been successfully used as a noncontacting tool for strain and vibration studies, depth-contour mappings, and transient/dynamic phenomena analyses. In the area of nondestructive testing, holographic interferometry has been used to detect and locate disbonds within honeycomb-sandwich structures; disbonds between steel cylinder and diffusion-bonded aluminum cladding; flaws within either passenger car or aircraft tires; cracks in projectile bodies; and also to separate hollow turbine blades according to wall thickness. Holographic interferometry has also been used for monitoring stress corrosion cracking and for the determination of Young's modulus for glass. Complete holographic test systems are presently commercially available from approximately twelve manufacturers, while the necessary components required to custom build a system are available from a multitude of sources. The overall price of a laboratory test system varies in direct accordance with the sophistication, capabilities, and object size and spans the price range of $1,500 to $25,000. Highly specialized industrial holographic analyzers are also available at proportionately higher prices. Photographic examples of holographic testing systems and materials evaluation applications can be found in Figures 28 to 52. These photographs are augmented by either self-explanatory or annotated captions* so as to obviate the need for any further prolonged discussion here in the body of the text. As for the interferometric results, it should be noted that the greater the fringe density, the greater is the surface deformation which produced it.

ACOUSTICAL HOLOGRAPHY

Acoustical holography is another endeavor which has been vigorously pursued for nondestructive testing purposes, since sound, unlike light, is capable of penetrating opaque objects. Acoustical holography, like optical holography, is a two-step technique involving the processes of acoustical hologram construction and reconstruction. In the construction process, the acoustical hologram may be

*In these captions, the frequently used designation *Holographic Nondestructive Testing* appears in abbreviated form as *HNDT*.

formed either directly by the interference of an acoustical *object* beam with an acoustical *reference* beam in the acoustical domain, or indirectly via the interaction of a piezoelectrically detected acoustical object beam with an electronically simulated reference beam. With respect to the reconstruction process which must occur in the optical domain in order to be seen, the particular method involved will be the determining factor as to whether the reconstruction process occurs *coincidentally with* or *ensuing to* the process of construction. The specific methods used for acoustical hologram generation are depicted in Figure 53. In addition, representative geometrical diagrams portraying these methods have also been included as integral supplements in Figures 54 to 60 and 64 as the differences between these methods stem predominantly from differences in the geometrical arrangements of the components used to construct the acoustical holograms. As can be seen from Figure 53, the various techniques developed thus far fall into two general categories; namely, *real-time* and *raster-scanning*. For the most part, acoustical analogs of existing optical holographic methods have been employed wherein the acoustical portion of the system is submerged in a liquid medium, usually water, and the electro-optical portion required for readout purposes is situated externally to the liquid tank. Although higher acoustical frequencies have been used in specialized instances, the majority of work, for practical testing applications, has been performed in the 1-10 MHz frequency range.

Real-Time Acoustical Holography: In the construction process, the acoustical hologram is formed on a liquid surface as a relief pattern of variable height. The simplified surface conditions and equations associated with this approach are included in Figure 54. A basic liquid-surface system for acoustical holography is shown in Figure 55. This figure is augmented by Figures 56 and 57 which illustrate the physical nature of the liquid surface relief pattern — the acoustical hologram — and the types of readout obtainable with this method. It should be noted that the technique shown in Figures 56 and 57 preceded in time the one illustrated in Figure 55, and hence did not incorporate improvements such as the use of the small isolation tank and acoustical lenses. The relief pattern is produced by the interference effects of two interacting beams of either continuous or pulsed ultrasound — one which has been transmitted through the test object, the *object beam*, and the other, the *reference beam*, which has been directly transmitted to the liquid surface. Reconstruction of this acoustically formed hologram occurs simultaneously for all practical purposes and is accomplished by reflecting light, incident from above, from the surface. A spatial filter is used to achieve a separation of the resulting diffracted light into components for viewing and recording purposes. Because all of the liquid surface elements comprising the acoustical hologram are formed at the same instant, the reconstruction process can be accomplished in quasi real-time. This important characteristic enables test objects undergoing examination to be continuously moved and rotated for defect enhancement purposes and the resulting dynamically changing images to be recorded by appropriate auxiliary instrumentation. The use of acoustical lenses results in the further enhancement of image quality and permits the interrogation in depth of preselected subsurface layers of test object material. For this method, the maximum obtainable acoustical field of view to date is of the order of five and one-half inches. Finally, this method is presently restricted in the acoustical domain to the application of the through-transmission mode and is, for the most part, subject to the attendant limitations of this particular technique.

Raster-Scanning Acoustical Holography: This method of acoustical holography can be further subdivided into two basic approaches — electronic raster scanning and mechanical raster scanning as in Figure 53. In this method, energy must be transformed initially from acoustical to electronic, and subsequently from electronic to light. In the construction process, ultrasonic fields which have been either transmitted through or reflected from the test object are sensed by piezoelectric detectors. These detectors may be of relatively moderate surface area, such as those that are used as receiver faceplates for electronically-scanned ultrasonic image converter tubes, or they may be of the point-receiver type, such as those that are used in mechanical raster-scanning systems. The manner in which an acoustical hologram is constructed by the mechanical raster-scanning technique is illustrated in Figure 58. By detecting ultrasonic fields of interest using piezoelectric means, the requirement for effecting the interaction of the object and reference beams to produce interference may be accomplished in either the acoustical or electronic domains. For the acoustical domain option, a real acoustical reference beam is used, while for the electronic domain option, a simulated electronic reference beam is used to interfere with the electronic signal derived from the piezoelectrically-transformed acoustical object beam. Upon achieving interference, the resulting electronic data is appropriately processed and used to modulate the intensity of either a point light source, the electron beam of a television display monitor or of an oscilloscope, or the writing element (single-turn wire helix) of a facsimile recorder. For the electronic raster-scanning systems, the electron beams of both the ultrasonic image converter tube and the television display monitor are in synchronization with one another, while for the mechanical raster-scanning systems, the point light source or the oscilloscope electron beam is scanned in synchronization with the piezoelectric receiver. The end result is the generation of an optical transparency which serves as the hologram (the optical equivalent to the acoustical hologram) for reconstruction in the optical domain. An example of a mechanical raster-scanning approach employing an electronically-obtained simulated reference beam for acoustical hologram construction is the synthetic aperture method wherein the object beam for the electronic domain is piezoelectrically derived from only a single scanning transducer, usually of the focused variety, being operated in the pulse-echo mode. With this method, it is possible to obtain, within limits, depth-indicative acoustical holograms of subsurface layers of the isonofied test object. Additional examples of mechanical raster-scanning methods, as per Figure 53, are included in Figures 59 and 60. Examples of raster-scanned acoustical holograms are shown in Figures 61 to 63, and the subsequent reconstruction process is depicted in Figure 64.

In terms of reduction to practice, both the real-time and raster-scanning acoustical holographic methods are capable of achieving the resolution expected on the basis of the wavelength and hologram aperture used. While mechanical raster-scanning methods are two-step processes, the real-time liquid surface method is essentially a one-step process — the processes of hologram construction and reconstruction occurring almost simultaneously. In addition, while it is possible to generate acoustical holograms with commercially available equipment employing the electronic raster-scanning method, the only complete acoustical holographic systems designed specifically for materials evaluation applications available to date employ either the inherently simple real-time liquid surface, or synthetic aperture mechanical raster-scanning methods. The cost of complete systems such as these is presently of the order of $40,000.

Regarding practical nondestructive testing applications,[619-639] much of the developmental work was performed with laboratory-type test specimens. However, the real-time liquid surface method is currently being applied to detect delaminations and inclusions in graphite-epoxy and boron-epoxy lamina; debonds in metal-nonmetal and metal-metal structures including honeycomb-sandwich panels; voids in diffusion-bonded structures; and fatigue cracks in steel. Acoustical holography, like acoustical imaging, provides optimum test results using objects possessing simple surface geometries. Objects possessing complex surface geometries still constitute significant impediments to the more widespread application of this technique. However, efforts are now being made to mitigate these impediments through the development and application of cylindrical and mosaic-type acoustical transducers. Several representative examples of results obtained using methods of liquid-surface acoustical holography are shown in Figures 65 to 67.

ELECTRON HOLOGRAPHY

Only a few pertinent comments will be made at this time concerning the remaining holographic technique, electron holography, for the sake of completeness. Although electron microscopy has become one of the most important tools of modern day science, electron holography has within the short time span of twenty years caught up with electron microscopy as an imaging method.[74] This accomplishment was made possible by a significant breakthrough made in 1968 by a group of Japanese scientists.[167] Electron holography now has a resolution equivalent to that obtainable with electron microscopy. As for utilization, the specific application is the ultimate determining factor as to which of these two methods should be used. In certain instances, electron holography would be preferable, while for others, the method of choice would be electron microscopy.

HOLOGRAPHY SUMMARY

In summary, holography has undergone a rebirth and maturation during the decade of the sixties. Further advancements remain to be made in the areas of the development of new and improved coherent sources of radiation; the development of new and improved holographic recording materials exhibiting increased sensitivity, higher resolution, faster speed, greater dimensional stability, more faithful reproducibility of multicolor scenes, and reusable capabilities; the development of improved fringe interpretation techniques; the development of improved techniques for increasing the range of variation in sensitivity of holographic interferometric methods; and, finally, the improvement and simplification of the reconstruction process involving the suppression of image granularity and the utilization of limited coherent white light sources. The ultimate success of holography as a practical scientific tool will be directly dependent upon the contributions derived from the continuing explorations of world-wide research and the attainments of further progress in areas of current application.

MICROWAVES

Microwaves are a form of electromagnetic radiation comprising a not-too-rigidly defined frequency band of 0.225 to 100 gigahertz (1 GHz = 10^9 Hz) and a

corresponding wavelength band in free space of 133.3 to 0.3000 centimeters. In the electromagnetic spectrum, the microwave frequency band is bounded by the lower frequency radiowave band on the one hand, and by the higher frequency infrared band on the other. The microwave frequency bands are delineated in Figure 68. In certain respects, microwaves behave like light waves in that they travel in straight lines, reflect, refract, diffract, interfere, and scatter according to the laws of optics. Differences in behavior do arise due to differences in wavelength — microwaves typically possessing wavelengths some one hundred thousand times larger than light. As a direct consequence, microwaves tend to interact with objects and materials on a macroscopic scale and light on a microscopic scale. Unlike light, microwaves are capable of penetrating most nonmetallic materials and structures, reflecting and scattering from internal boundaries, and interacting with the molecules of materials. Although its significance as a materials testing method was recognized in the early 1950's, microwave technology was not extensively put into practice as a nondestructive testing tool until the 1960's. This advancement was made possible by the advent of more adequate equipment for the generation and measurement of microwave energy.

To date, all microwave techniques have employed either continuous-wave or frequency-modulated modes of radiation, as the problems associated with the reduction-to-practice of pulse reflection techniques similar to those used in ultrasonic testing are quite formidable. An insight into these problems can be obtained by merely considering the distance that a microwave pulse would occupy in free space. Since the velocity of propagation of electromagnetic radiation is 3×10^8 meters per second, a 1-microsecond pulse would occupy 300 meters in space, a 1-nanosecond (10^{-9} second) pulse 30 centimeters, and a 10-picosecond (10^{-11} second) pulse 0.3 centimeter. Thus, with present day technological know-how the attainment of a bona fide range resolution capability for flaw detection purposes in microwave nondestructive testing, although highly desirable, is a physical impossibility. Whereas magnetrons, klystrons, traveling wave tubes, paramagnetic oscillators, and molecular oscillators may all be used for the generation of microwaves, it has been the klystron which has proven to be the workhorse of microwave nondestructive testing. In materials testing applications, shorter wavelength radiations spanning the wavelength interval of 0.5 to 20 centimeters (1.5 to 60 GHz) have been employed in order to achieve improvements in defect-size resolution.

When microwaves penetrate a nonelectrically conducting material, they are influenced by only three parameters of the material — two electromagnetic, the *dielectric constant* and the *loss tangent*, and one geometric, the shape and dimensions of the material. The dielectric constant, also referred to as the *permittivity*, is in actuality a frequency-dependent parameter that is a measure of the amount of electrostatic energy that can be stored per unit volume of material when a unit voltage is applied and, as a consequence, is intimately associated with the polarization characteristics of the material. Polarization always occurs to some degree whenever microwaves penetrate dielectric materials, since electrical charge within the material is displaced due to the influence of the electric field associated with the microwaves. The other electromagnetic materials property, the *loss tangent*, is a measure of the amount of power which is lost as heat whenever a dielectric material is subjected to a high frequency electromagnetic field. Both the dielectric constant and loss tangent are functions of material composition, structure, homogeneity, orientation, moisture content, and other

similar factors. These relationships lead to a number of interesting practical microwave nondestructive testing applications. As for the shape and dimensions of the material, if the surface geometry is too irregular, the physical extent too small, or the thickness too great, then deleterious effects, such as undesirable surface reflections, objectionable edge effects, a distortion of beam directivity, and excessive self-absorption by the material of microwave energy, may be encountered.

The specific geometric methods that have thus far been employed in microwave nondestructive testing are illustrated in Figure 69 and include:

Transmission where microwave energy passing through the material is accordingly modified by the internal condition of the material.

Reflection where the microwave energy reflected from either the surface or from within the material is correspondingly modified by either the surface or internal condition of the material.

Scattering where microwave energy penetrating the material is randomly reflected and/or diffracted by scattering centers, such as cracks, voids, inclusions, and foreign material, situated within the parent material.

Interferometry where two or more sets of microwave wavetrains simultaneously traveling in either the same or opposite directions naturally interfere with one another as in the classical case, or where two sets of microwave wavetrains are deliberately made to interact with one another to produce interference as in the holographic case.

Block diagrams of the equipment associated with the specific geometric microwave methods are included in Figures 70 to 76.

Microwave signal data displays for nondestructive testing applications are shown in Figure 77. In certain established test approaches, the amplitude and/or phase of a microwave signal is measured and/or monitored using either meters, oscilloscopes, or recorders. In more sophisticated test approaches, a spectral analysis is performed on the detected microwave signal to yield additional information concerning flaw parameters and physical properties. As in other nondestructive testing techniques, methods are available for displaying the data in pictorial form in an attempt to yield perceptible defect profiles and simplify the interpretation of microwave test results. These methods include:

Field Scanning where a microwave field is probed with a scanning pickup horn moving in synchronization with an intensity-modulated writing element of the recording instrumentation, such as the single-turn wire helix of a facsimile recorder or the electron beam of an oscilloscope. The end result is a plan view display of the cross section of the microwave field containing variations in contrast which are in direct proportion to the strength of the detected signal.

Cholesteric Liquid Crystals where a mapping of the entire microwave field, or a large fraction thereof, is obtained in color with liquid crystals by their ability, upon exposure, to convert the microwave energy absorbed as heat into a temperature-dependent wavelength readout. Because of the nonuniformities inherent

within the microwave field, the surface of a cholesteric liquid crystal detector — a thin layer of liquid crystals deposited on a thin black substrate — will be differentially heated in direct accordance with the variations of intensity of the microwave field to yield a color pattern, representing the desired mapping. The color change is reversible with respect to temperature and may be effected over a narrow and variable temperature range.

Photographic Emulsions where a microwave-field mapping is obtained in either black-and-white or color by using appropriately prepared photographic films as sensing elements. As with the cholesteric liquid crystal method, the differential heating effects associated with the microwave field are relied upon to produce the thermal gradients required for the recording, which in this case is irreversible. The film is usually subjected to an initial and incomplete exposure to uniform illumination with light, coated with a thin film of developer, and then placed into the microwave field to undergo further development. Because the rate of development of a photographic emulsion is temperature-dependent, those regions of the film that are exposed to more intense microwave radiation will experience greater heating effects and will consequently develop more rapidly than those regions exposed to less intense levels of microwave radiation. When the exposure is completed, the degree of darkness within the recording will vary in direct accordance with the intensity of the microwave field.

Holography where the visualization of a highly frequency-stable microwave field is accomplished through a two-step method involving the processes of construction and reconstruction. In the construction process, a known and reproducible microwave beam is allowed to combine and deliberately interfere with an unknown, mutually coherent, and complex microwave beam. The known beam is referred to as the *reference beam*, the unknown beam is referred to as the *object beam* and is derived from the same microwave source. The resulting interference pattern is then recorded using a suitable recording medium. When a real microwave reference beam is employed to create interference in the microwave domain, recording media exhibiting temperature-sensitive characteristics such as cholesteric liquid crystals and carbon-impregnated paraffin have been found to be satisfactory. For this type of approach, the construction process is completed by generating an optical transparency of the microwave hologram, where the optical transparency is in actuality an optical hologram. The necessity of effecting a hologram translation from the microwave to the optical domain can be obviated by using an alternative approach. In this case, an electronically simulated microwave reference beam is allowed to interfere with an electronically transformed object beam derived from a probe being used to scan the microwave field of interest. The resultant signal created by the interference, now occurring in the electronic domain, is used to modulate the intensity of a point light source moving across a photographic plate in synchronization with the probe. The end result is the production of a single optically scanned hologram containing extraneous information in the form of a recorded, raster-scanned, line pattern. In the reconstruction process, coherent light from a laser is used to illuminate the optical hologram to yield an image of the object. Because the wavelength of the laser light is of the order of 10^{-5} times smaller than that of the microwave radiation, the reconstructed image is reduced by the same ratio and necessitates the use of an auxiliary optical system for viewing purposes. The reduction in image size also substantially diminishes the three-dimensional aspects normally associated with reconstructed holographic images. The techniques of holographic interferometry

may also be effectively employed for microwave visualization applications. In conclusion, holography essentially differs from the previously described methods in that the former methods utilize only amplitude information while holography utilizes both amplitude and phase information. Thus a microwave field is more completely portrayed with the holographic method. The methods of microwave visualization are still very much in their infancy with respect to nondestructive testing applications and it is likely that considerable development along these lines will be made in the immediate future.

An example of a microwave holographic system is shown in Figure 78 and will be discussed in detail to further familiarize the reader with the holographic method. In this particular technique,[672] a layer of carbon-impregnated paraffin coated with a thin aluminum reflecting surface initially serves as the object in the initial step involving the generation of a double-exposure optical hologram (a holographic interferogram). An optical hologram is generated in the conventional manner by recording the interference pattern produced by the interaction of the reference beam with an object beam which is reflected from the undistorted wax plate. The laser is then turned off and the microwave generator is turned on. The output microwave beam is divided into two mutually coherent beams by the directional coupler — a microwave reference beam which is used to directly illuminate the wax plate (the microwave holographic recording medium), and a microwave object beam which is used to directly illuminate the test object and to indirectly illuminate the wax plate to produce interference in the microwave domain. The microwave interference pattern is recorded through the distortions occurring at the wax surface resulting from the thermal expansion profile being produced by the differential absorption of microwave energy. The microwave is then turned off after a suitable exposure interval and the laser is turned on after the wax plate has cooled. A second exposure is then made of the distorted wax surface (the microwave hologram) and recorded on the original partially exposed optical hologram. In the optical reconstruction process, an image of the object is obtained accompanied by interference fringes resulting from the fact that each of the recorded holograms produces its own individual image and that the light waves associated with each of these images mutually interfere with one another.

The ways in which some of the specific geometric methods of Figure 69 have been used in combination with some of the signal data displays of Figure 77 are illustrated without any further comment in Figures 79 to 83.

A novel noncontacting method of measuring the depth of thin slots and cracks in both ferrous and nonferrous metals using microwaves is currently being developed[689,690,698] and will now be described, as there are many situations for which conventional nondestructive methods of measuring crack depth are insufficient. The technique utilizes the principle of eigenmode degeneration caused by surface discontinuities. Microwave power in the higher modes, such as the TE_{01} cylindrical or TM_{01} cylindrical, is generated in a circular waveguide and directed against a target surface which lies within the Fresnel zone of the coupling aperture. A slot or crack on the surface causes the power in the higher order mode to degenerate to the fundamental TE_{11} cylindrical mode which is then measured when the signal is passed through an appropriate filter to a meter or recorder. The system is depicted in Figures 84 and 85. The experimental data taken by irradiating aluminum and steel specimens containing mechanical calibrated

slots with either TE_{01} or TM_{01} cylindrical modes are shown in Figures 86 and 87. In both cases, the signal amplitude was referenced to the signal strength produced by the deepest slot irradiated with the TE_{01} mode. The uncertainty band in these figures arises from the lack of a good calibration procedure.

Microwave nondestructive testing techniques have been successfully used as a noncontacting tool for the detection of flaws such as inclusions, voids, and delaminations within nonmetallic structures; the measurement of contour, eccentricity, motion, and displacement involving either metallic or nonmetallic parts; the measurement of the thickness of coatings of one nonmetallic material over another or of a nonmetallic coating on a metal; the measurement of thickness of materials and structures bounded by parallel surfaces; the measurement of the degree of cure of plastic materials; the determination of moisture content of materials; the determination of the orientation of both metallic and nonmetallic fibers in fiber-reinforced nonmetallic materials; and the direct measurement of the dielectric constant and loss tangent, just to mention a few applications.[673-737] In spite of these impressive capabilities, microwave nondestructive testing is still handicapped by the following inadequacies: analysis of data can be difficult if more than one influencing variable is present; precise positioning of components is necessary to minimize interference effects; high frequencies which yield greater resolution are also more severely influenced by minor variations in materials properties; no standardized procedures are available for testing purposes; and finally, the method is still being explored and developed. Complete microwave nondestructive testing systems are currently commercially available from three manufacturers while the necessary components required to custom build a system are available from a multitude of sources. The overall price of a laboratory test system varies in direct accordance with the sophistication, capabilities, and accessories required and spans the price range of \$2,000 to \$25,000.

SAFETY

This technical monograph will now be concluded with a few remarks on the subject of safety. Generally speaking, whenever new technologies are introduced into recognized fields of endeavor, questions inevitably arise concerning the existence or nonexistence of safety hazards. The specific parallel in the case of this monograph is the introduction and reduction-to-practice of the relatively new technologies of holography and microwaves in the established field of nondestructive testing. For the most part, the hazards associated with the particular form of radiation are those which are of utmost concern. Once a safety hazard is recognized, adequate protective measures are taken to prevent unnecessary exposure of personnel to injurious levels of radiative intensity. In order to control the intensity of radiation, it is first necessary to place controls on the source of radiation. Once this is done, maximum permissible levels of exposure have to be determined. Other corrective actions involve the medical surveillance of personnel; the use of protective devices; the registration, supervision, and control of the radiation source; and finally, the reporting of accidents.

For optical holography, the effects of laser radiation are essentially the same as light generated by more conventional ultraviolet, infrared, and visible

light sources. The unique biological implications attributed to laser radiation are generally those resulting from the highly intense and characteristic monochromatic nature of laser light. Several of the existing regulative documents pertaining to holographic safety[538-541,740] are extremely interesting and should be read by anyone who becomes involved in holography. As for acoustical holography and microwaves, the output levels of the radiation sources, as used in nondestructive testing applications, are sufficiently low, and consequently do not pose any radiation hazards to personnel. In contrast, for microwave applications involving radar and communications systems, the power output capabilities of microwave generators are substantial and effective precautions are necessary. As for microwave safety, the reader is referred to the two representative publications included in the Reference/Bibliography Section of this monograph for additional reading.[738-739]

REFERENCES/BIBLIOGRAPHY

Attempts have been made, wherever possible, to facilitate the acquisition of reports and certain literature publications through the inclusion of accession numbers. On the whole, the accession number will be prefixed by either of three designations — AD, N, or A. Documents possessing accession numbers prefixed by AD or N are available at a nominal cost from the National Technical Information Service (NTIS), Springfield, Virginia 22151, while those with the A prefix are available from the Technical Information Service, American Institute of Aeronautics and Astronautics, Inc., 750 Third Avenue, New York, New York 10017. Certain other documents may also be obtained from the Superintendent of Documents, U. S. Government Printing Office (GPO), Washington, D. C. 20402.

Photographic Emulsions	Resolution Lines/mm	Emulsion Thickness (μm)		Exposure ergs/cm^2
		Glass	Film	
Kodak				
649 F	>3,000	17	6	1,000
High-Resolution Plates	>3,000	9	6	
SO-243	500	4		2
High-Contrast Copy	250	7		
AGFA-Gevaert Scientia				
8E56, 8E70, 8E75	3,000	6		200
10E70, 10E75	2,800	7	5	50
14E56, 14E70, 14E75	2,800	6		
14C70, 14C75	1,500	4		3
Ilford				
HE-NEI	>1,500	10		5
Polaroid				
55 P/N	—		—	—

Table I. PROPERTIES OF PHOTOGRAPHIC EMULSIONS USED IN HOLOGRAPHY TO PRODUCE EITHER ABSORPTIVE OR PHASE HOLOGRAMS [17, 74-80, 108, 169-178]

Variable	Tolerance
Film movement	$D/8$*
Path-length change	$(D/8)\cos(\theta/2)$**
Local pressure change	0.05 mm Hg
Local temperature change	0.31°F
Optical element movement	0.05μm
*D = fringe spacing	
**θ = shear angle	

Table II. TABLE OF TOLERANCES[199]

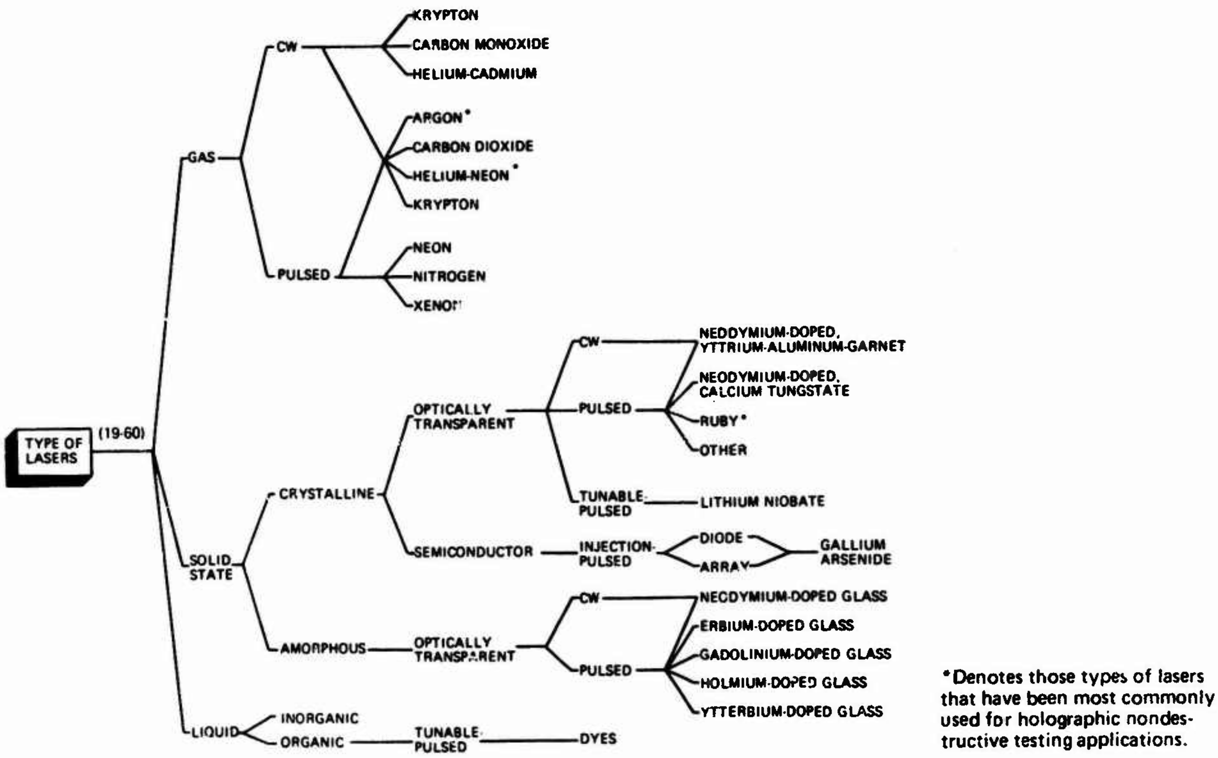


Figure 1. Types of Lasers

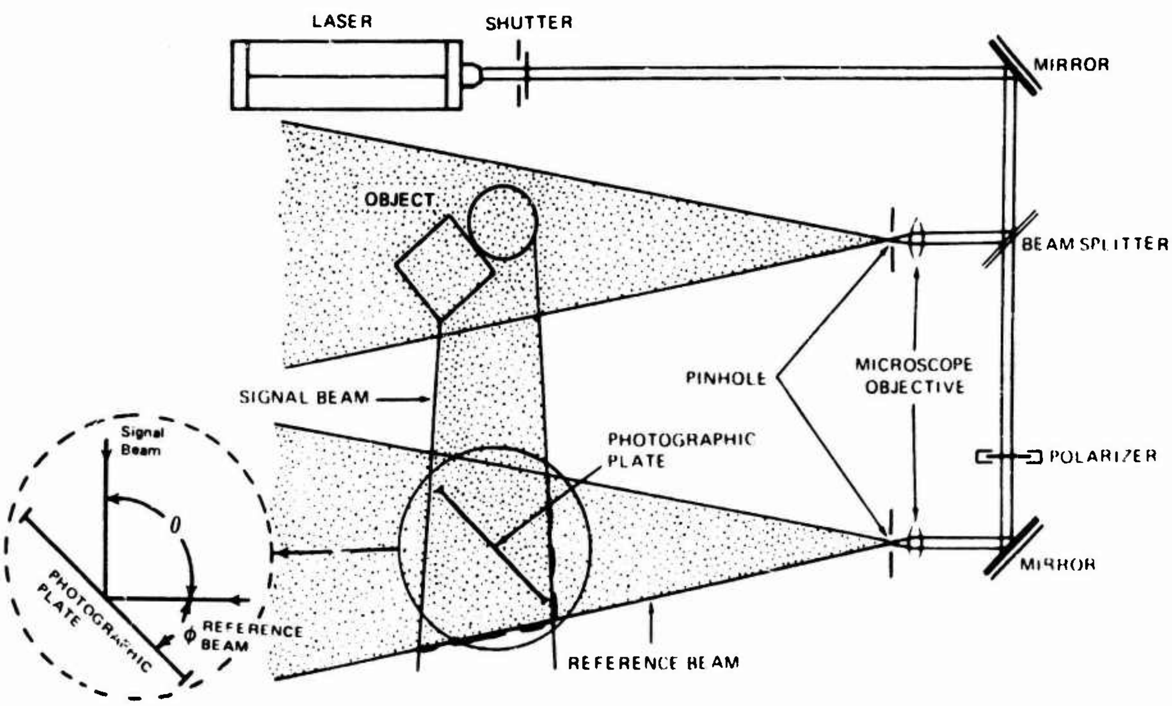


Figure 2. Hologram Construction

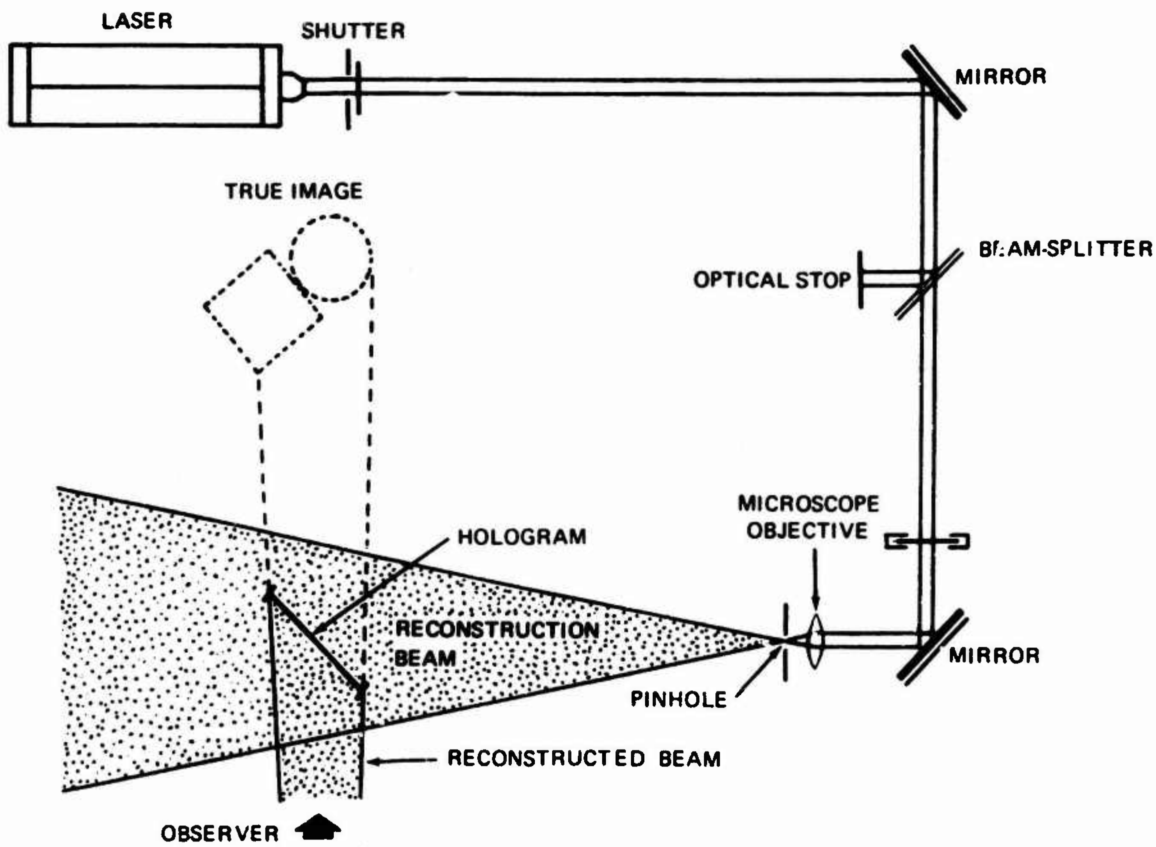


Figure 3. Hologram Reconstruction

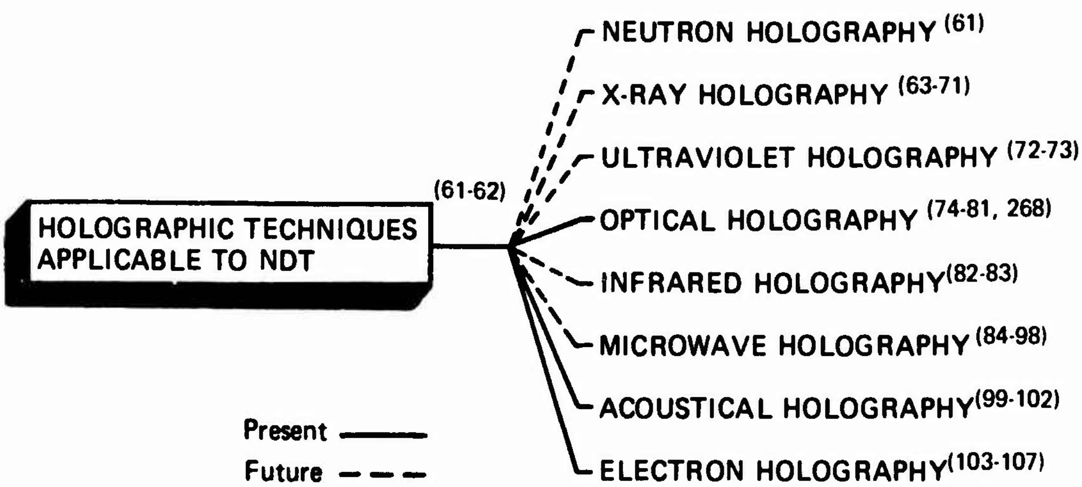


Figure 4. Present and Future Holographic Techniques Applicable to Nondestructive Testing

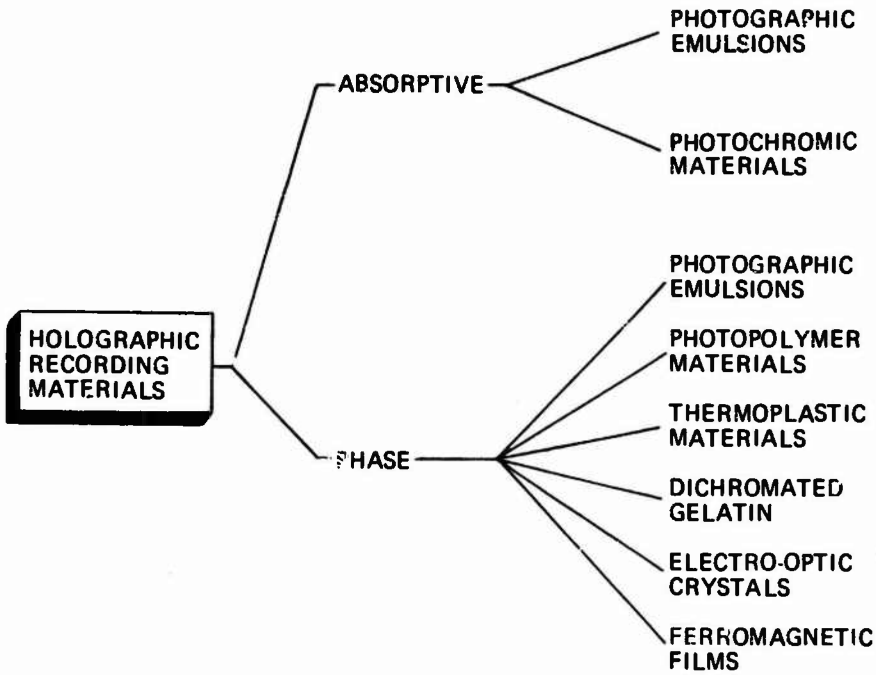


Figure 5. Holographic Recording Materials (17, 74-80, 108-151)

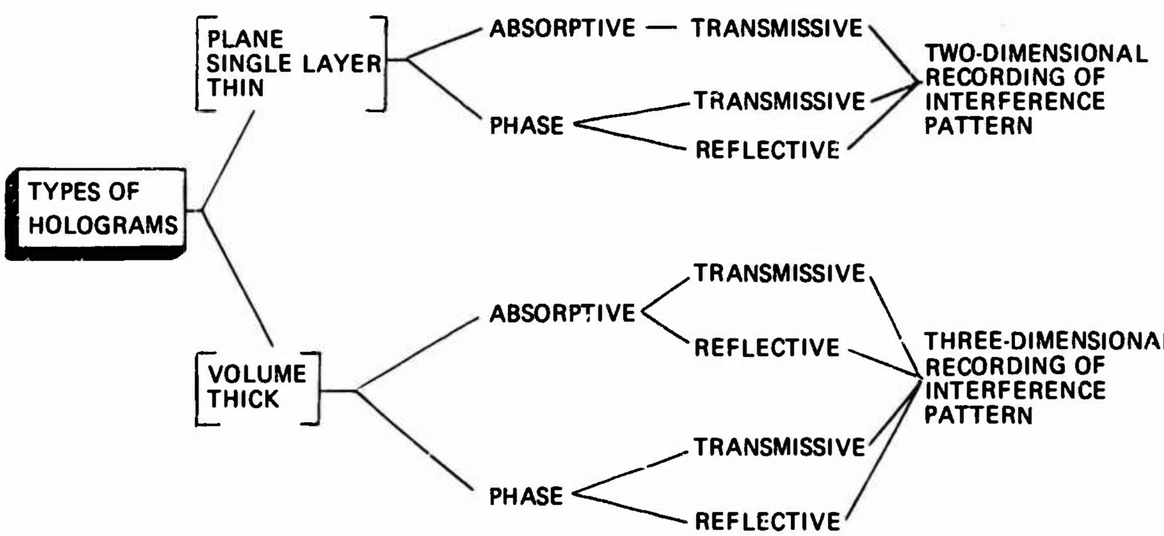


Figure 6. Types of Holograms (17, 74-80, 108, 152-168)

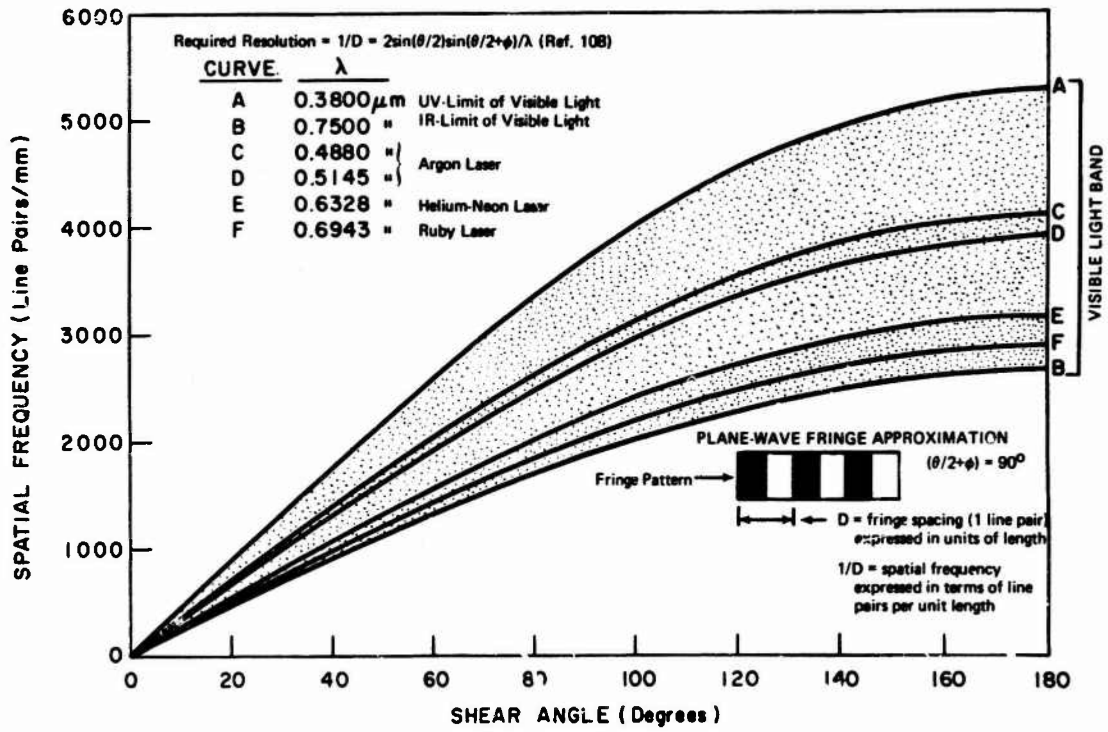


Figure 7. Spatial Frequency as a Function of Shear Angle for Plane-Wave Fringe Approximation

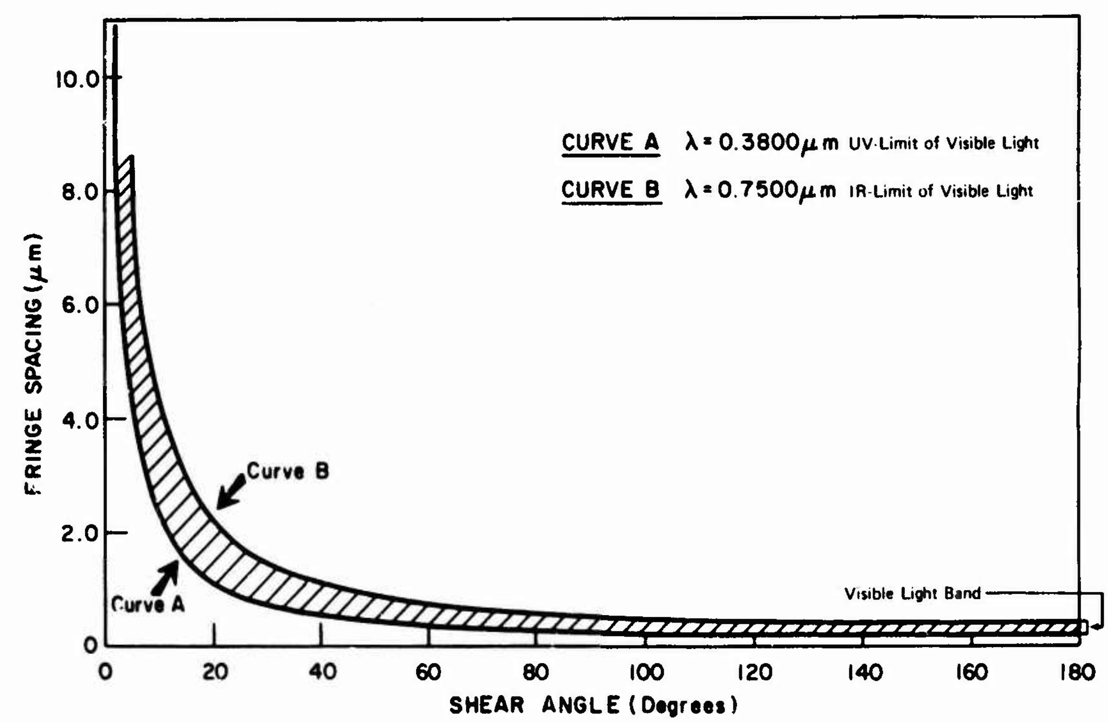


Figure 8. Fringe Spacing as a Function of Shear Angle
For Plane-Wave Fringe Approximation

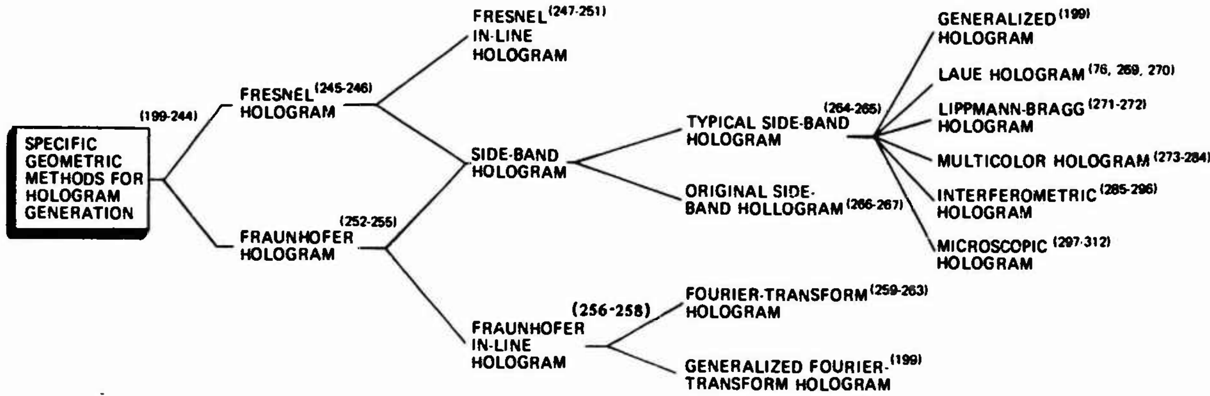


Figure 9. Specific Geometric Methods for Hologram Generation (17, 74-80, 108)

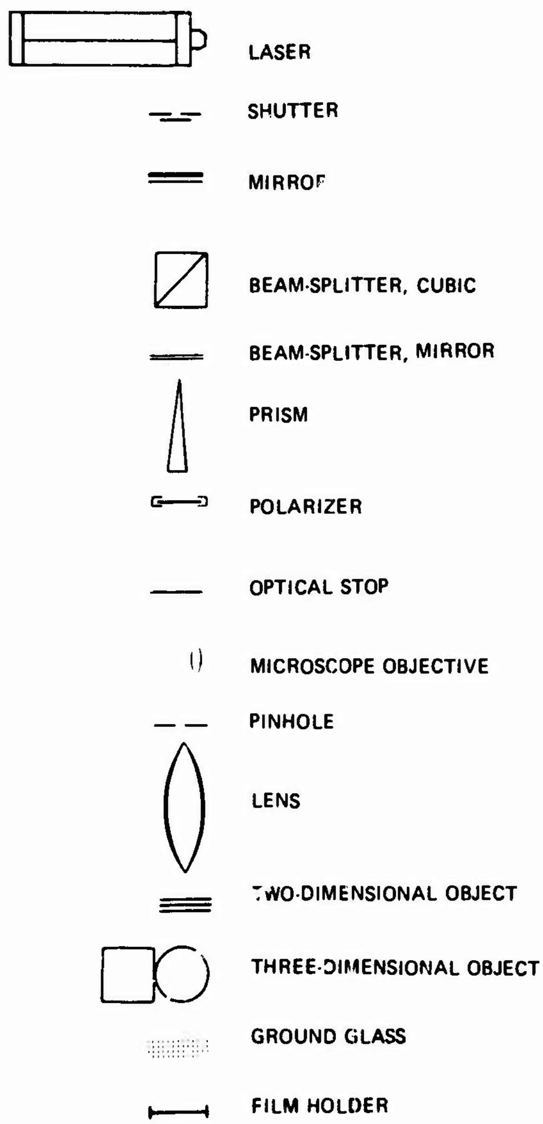


Figure 10. Graphic Symbols

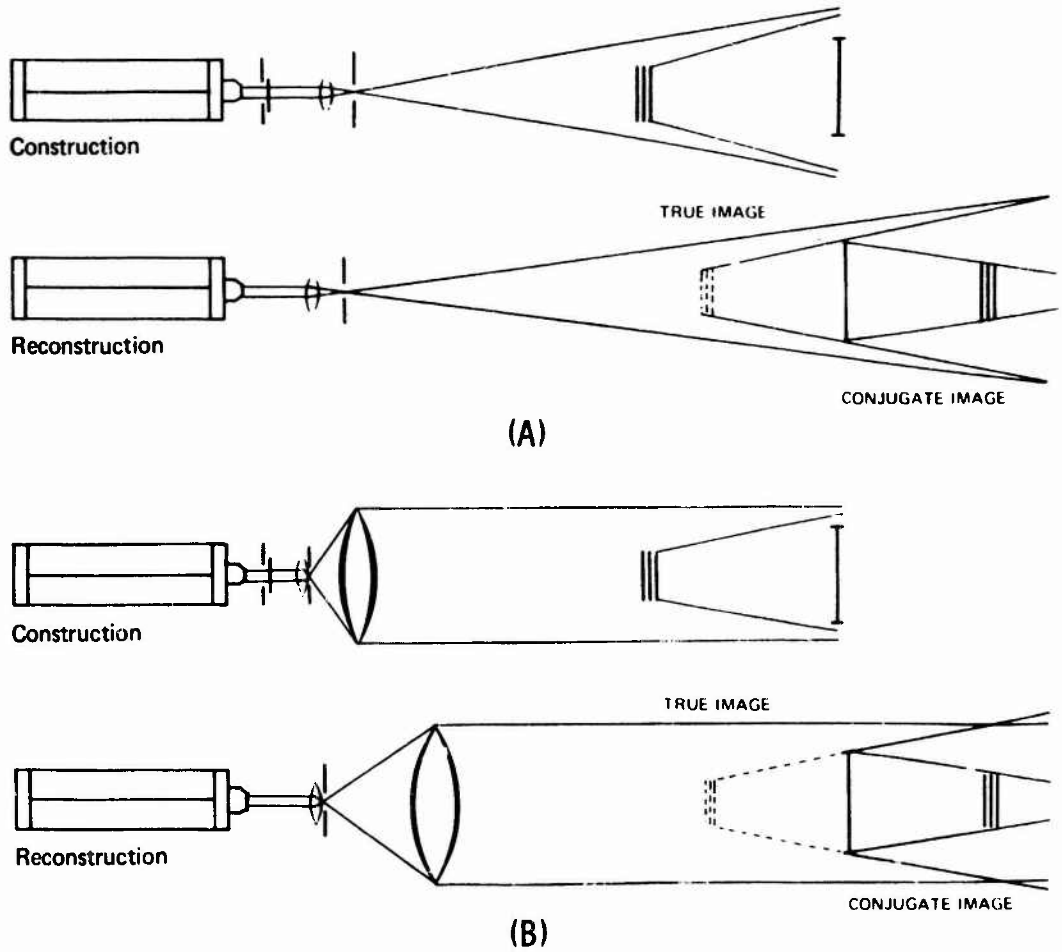


Figure 11. Fresnel In-Line Holograms Using (A) A Diverging Beam and (B) A Collimated Beam

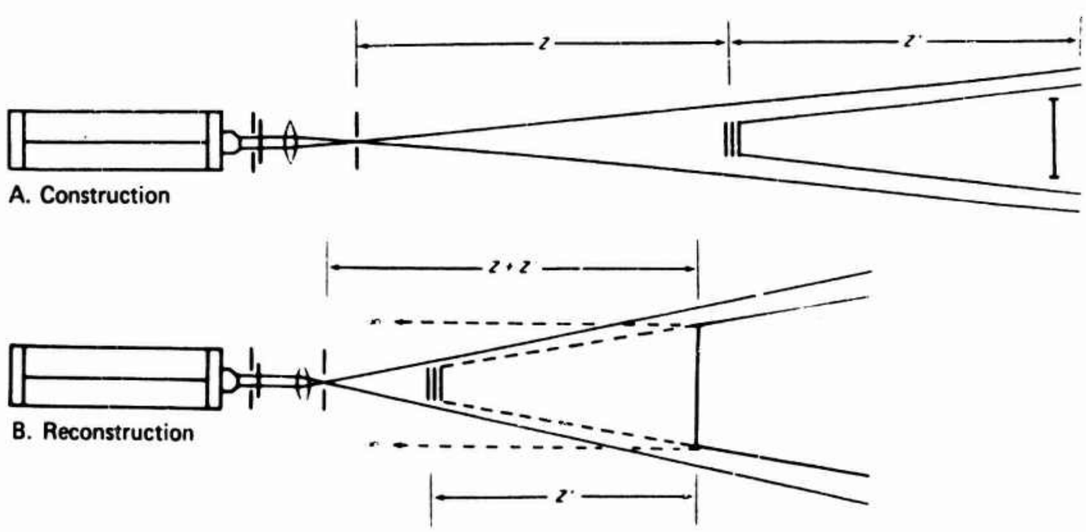


Figure 12. Fraunhofer In-Line Hologram Usinn a Diverging Beam

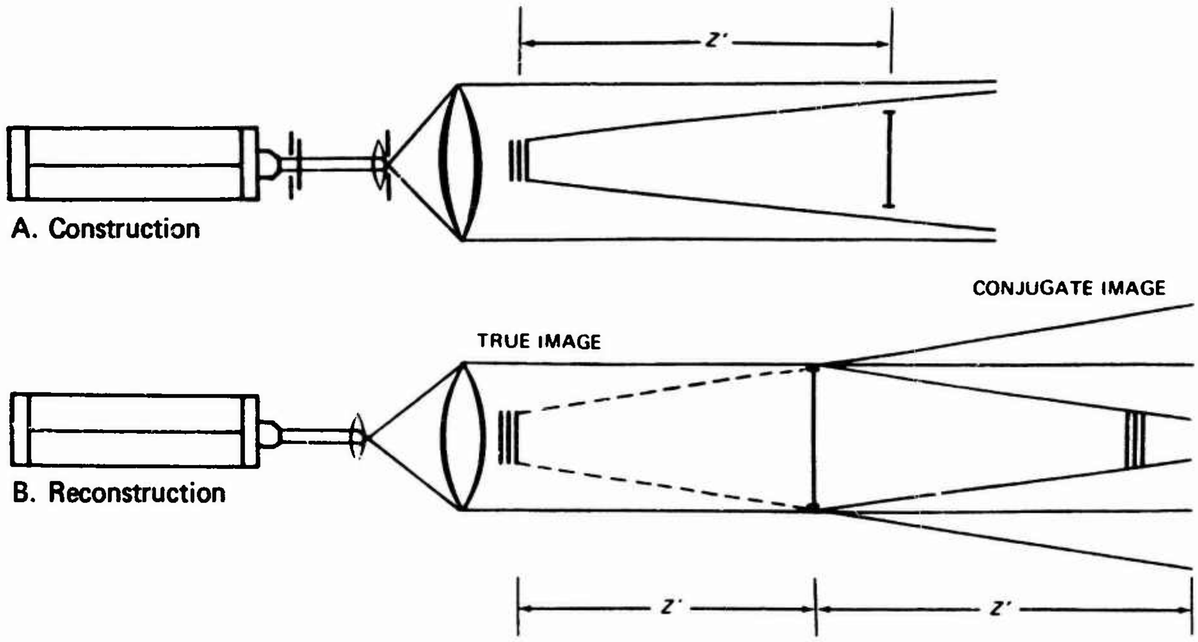


Figure 13. Fraunhofer In-Line Hologram Using a Collimated Beam

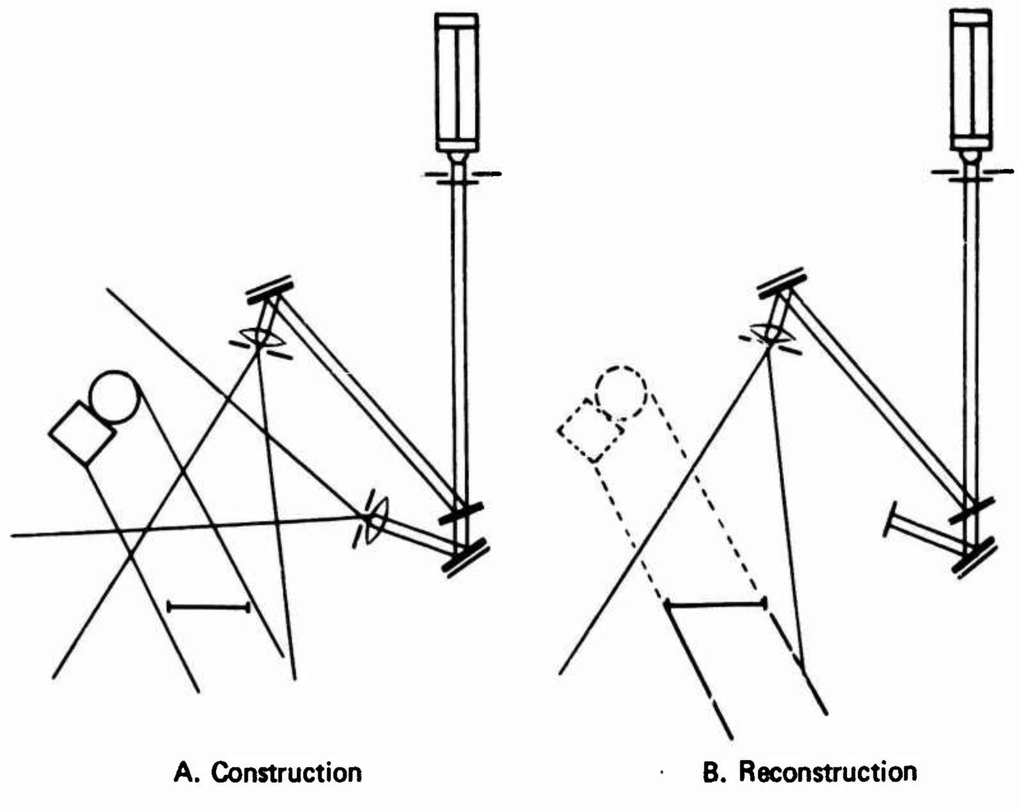
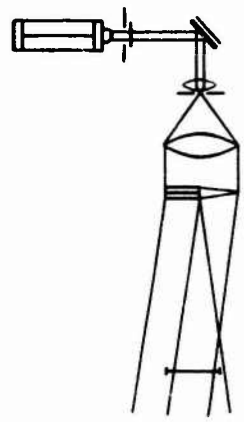
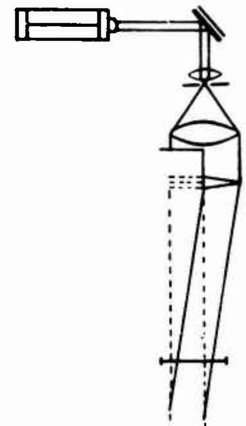


Figure 14. Typical Side-Band Geometry

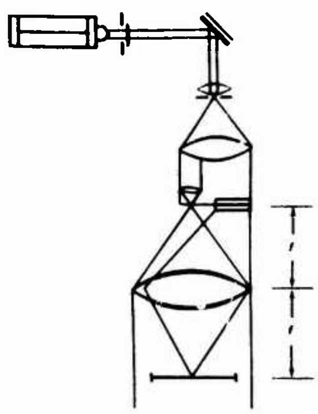


A. Construction

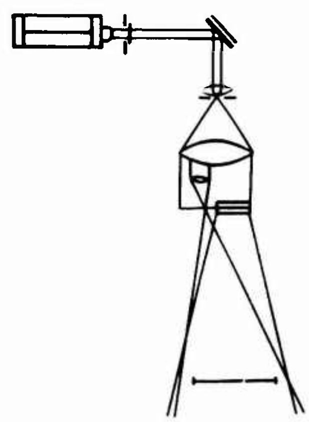


B. Reconstruction

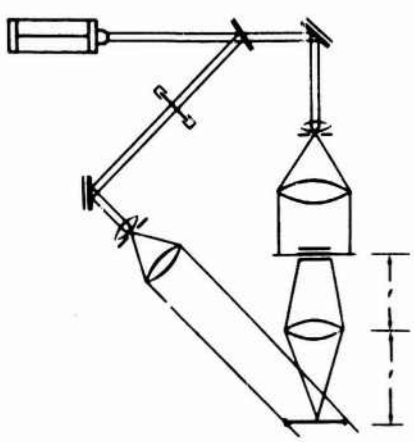
Figure 15. Original Side-Band Geometry



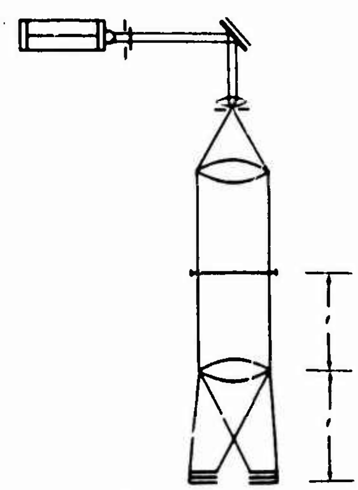
Fourier-Transform
Construction Geometry



Lens-Less Fourier-Transform
Construction Geometry

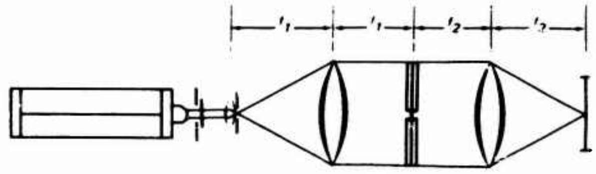


Side-Band Fourier-Transform
Construction Geometry

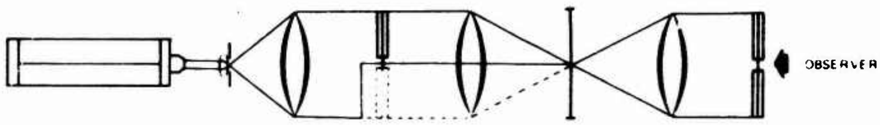


Fourier-Transform
Reconstruction Geometry

Figure 16. Fourier-Transform Hologram Geometries

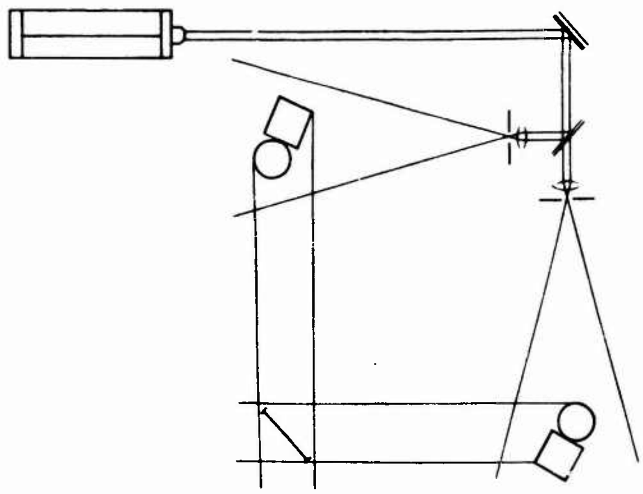


A. Construction

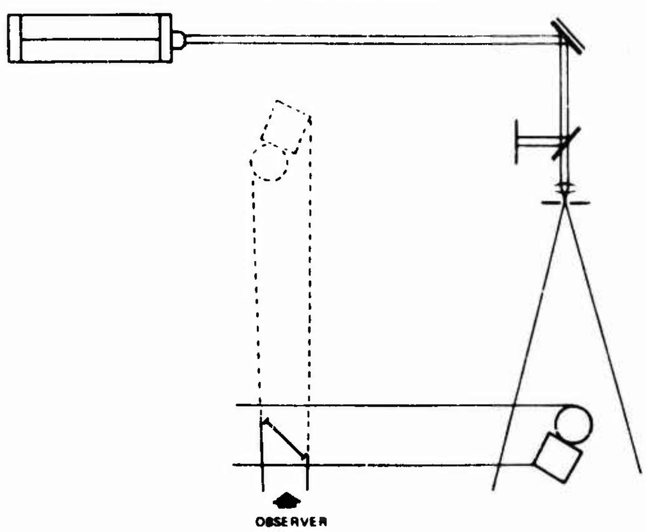


B. Reconstruction

Figure 17. Generalized Fourier-Transform Geometry

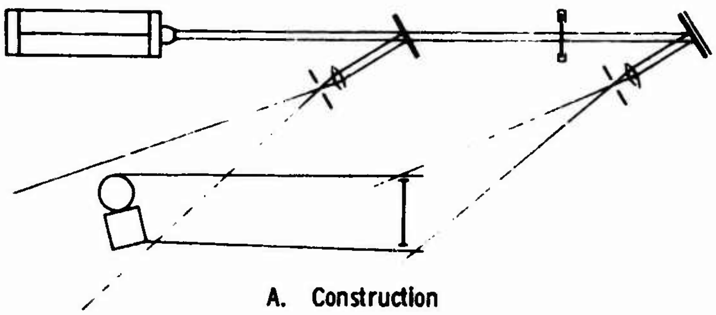


A. Construction

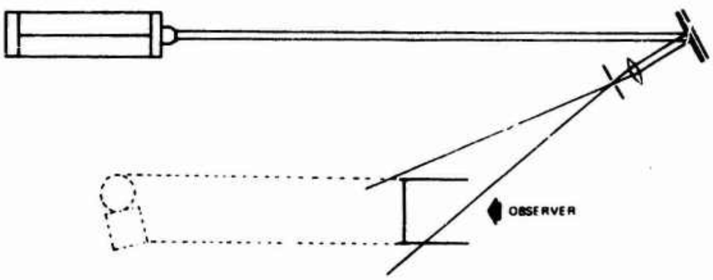


B. Reconstruction

Figure 18. Generalized Hologram Geometry

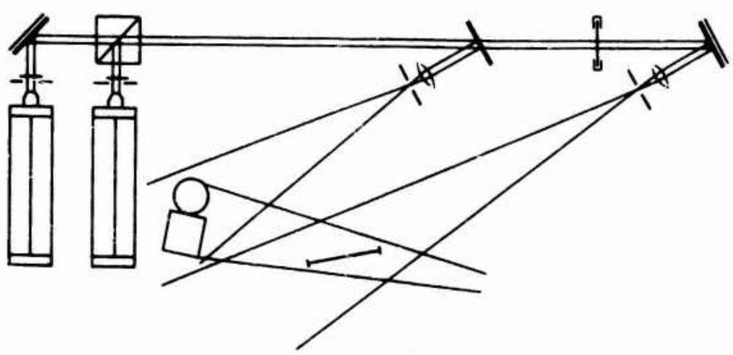


A. Construction

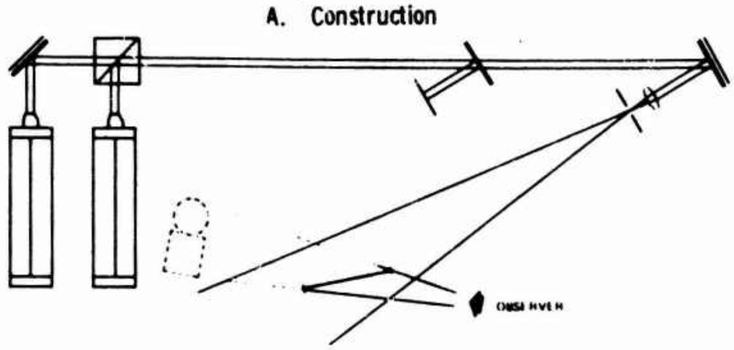


B. Reconstruction

Figure 19. Lippman-Bragg Geometry



A. Construction



B. Reconstruction

Figure 20. Multicolor Geometry

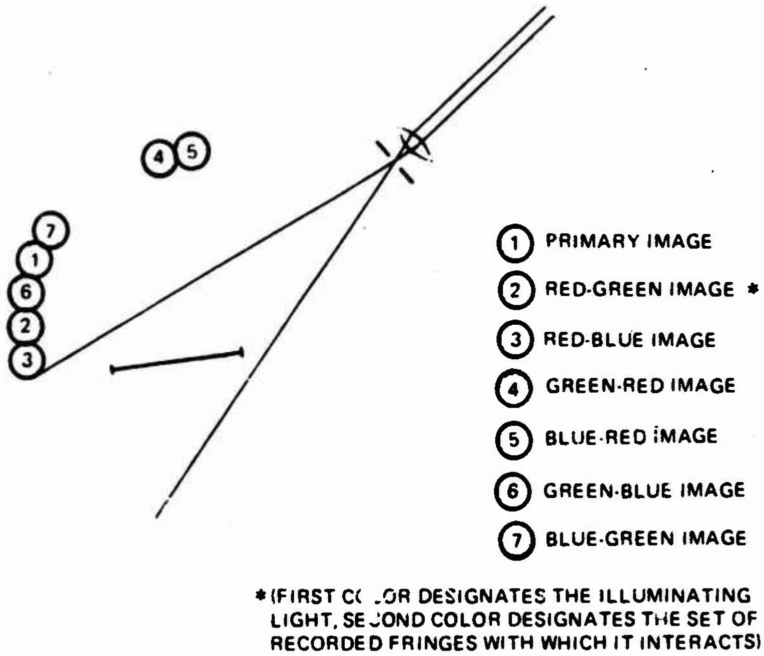


Figure 21. Positions of Ghost Images in the Reconstruction of a Multicolor Hologram

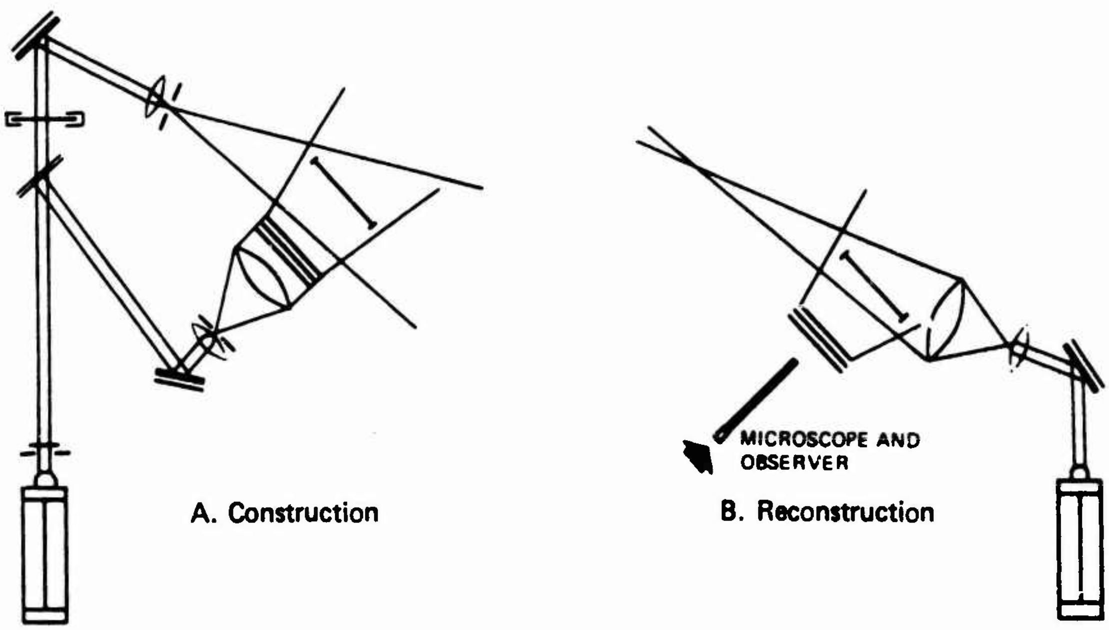


Figure 22. Geometry for Holographic Microscopy

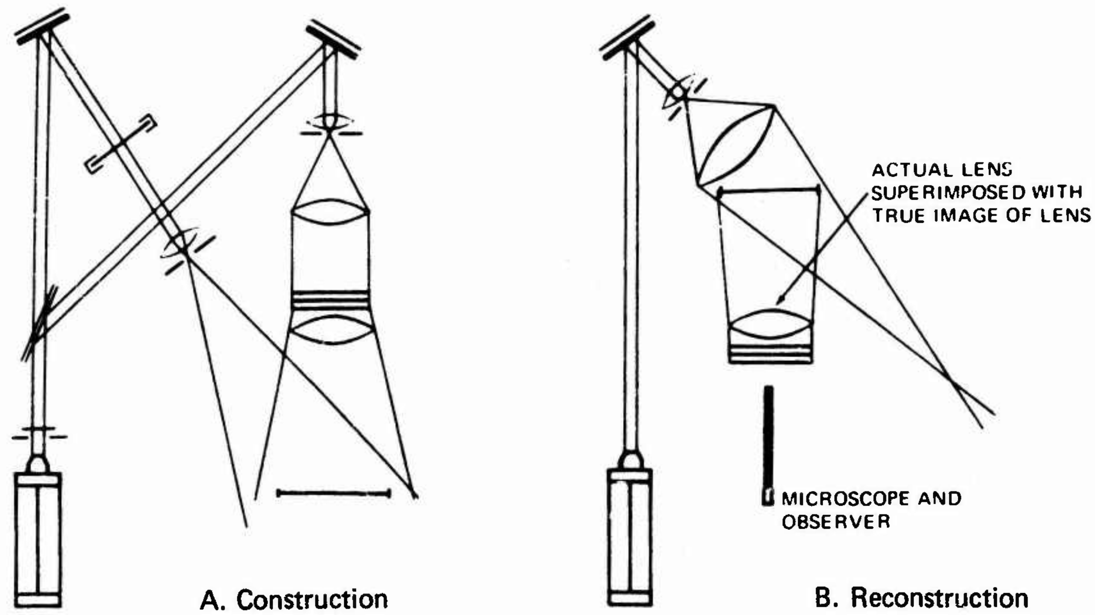


Figure 23. Holographic Microscopy with a Collecting Lens

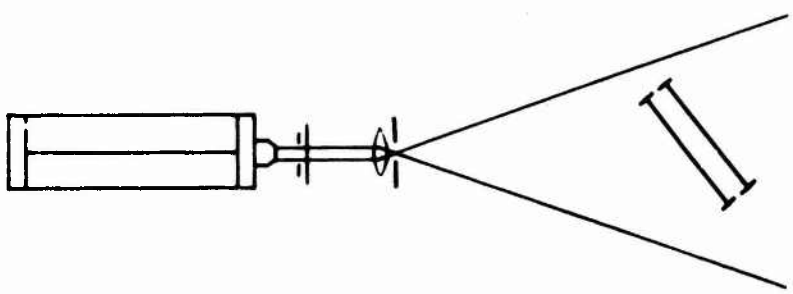


Figure 24. Hologram Copying Geometry(313-316)

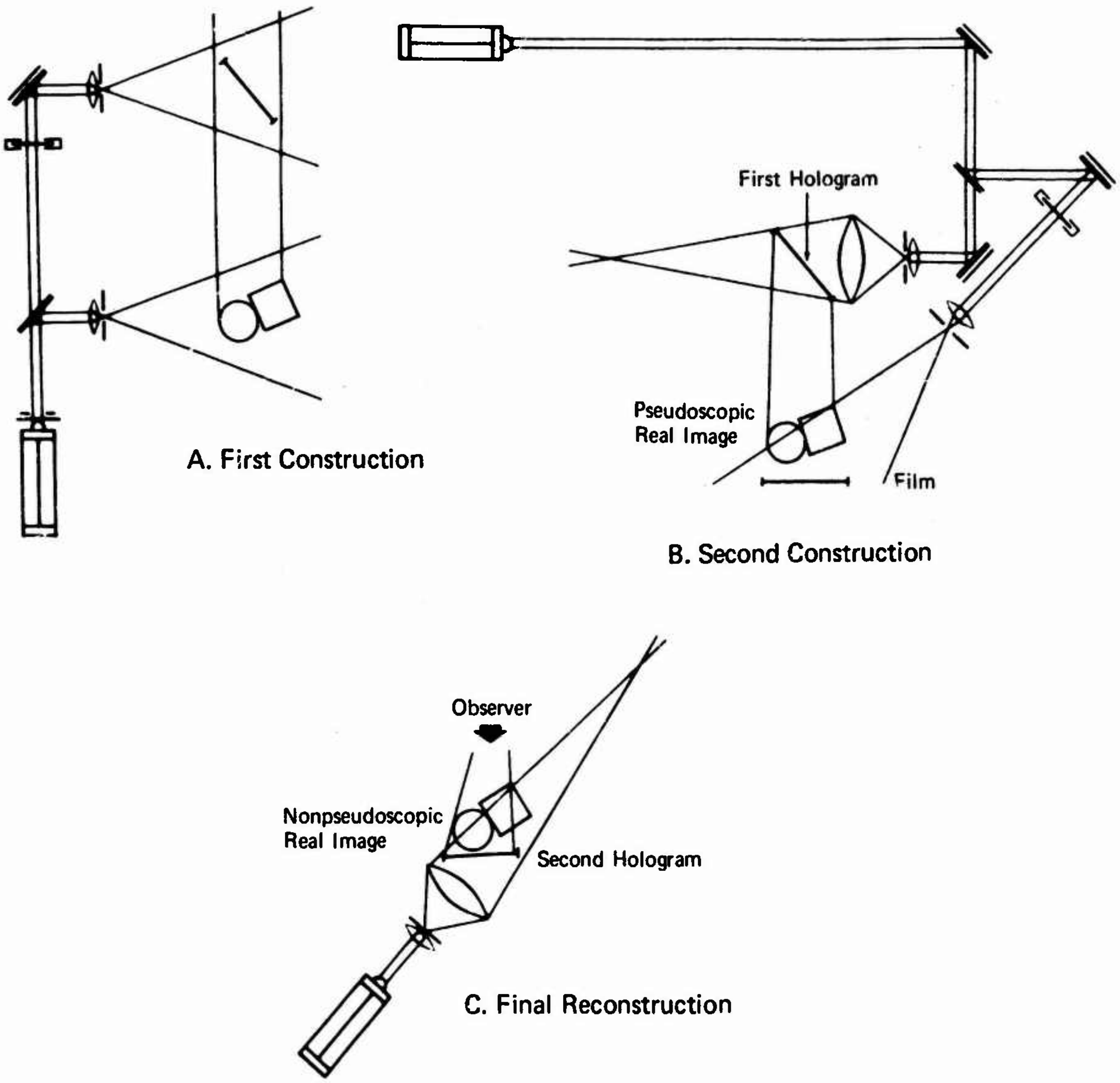


Figure 25. A Method of Constructing a Hologram Which Will Reconstruct a Nonpseudoscopic Real Image of a Given Object (317-319)

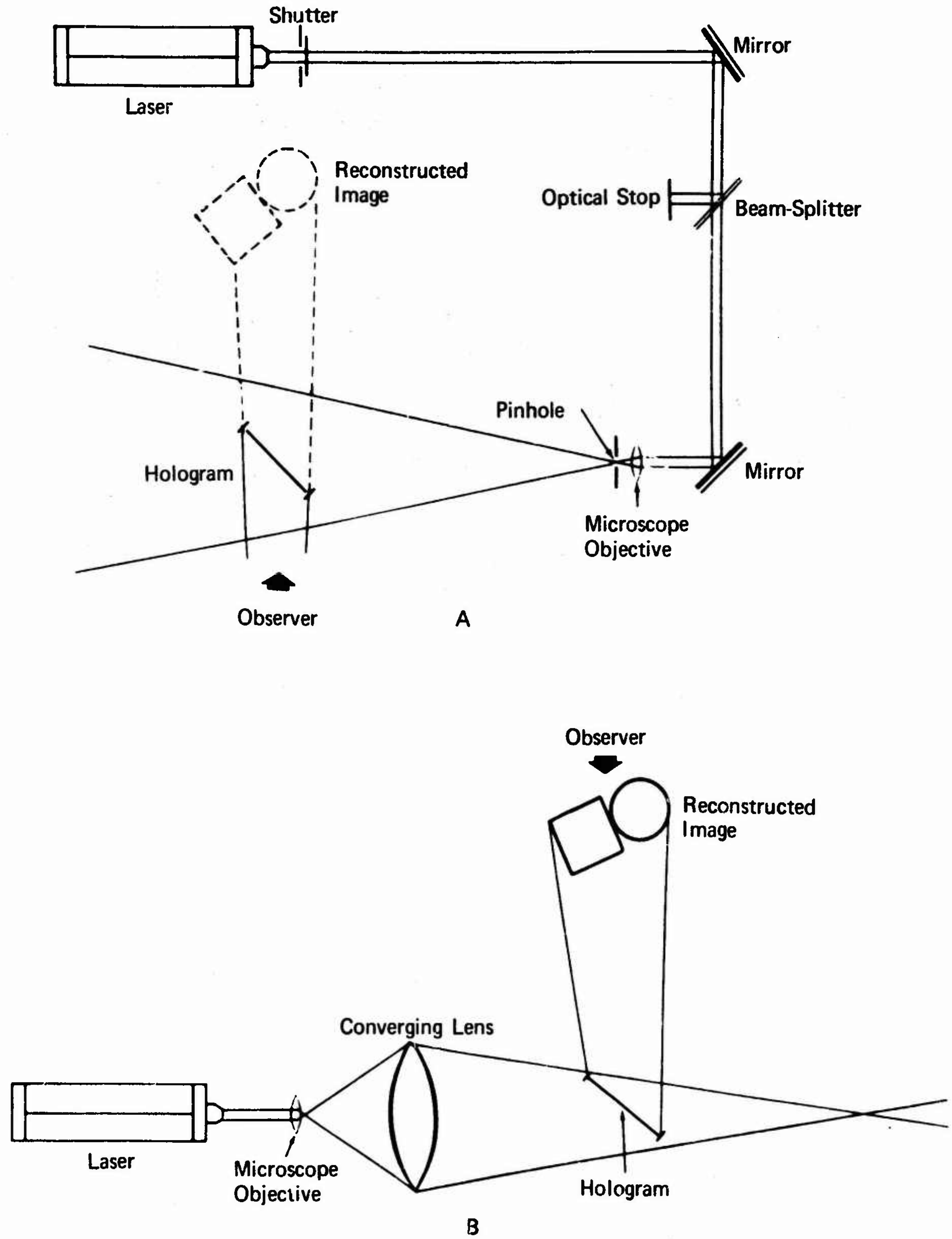


Figure 26. Reconstruction of the True Image: (A) Virtual Case; (B) Real Case

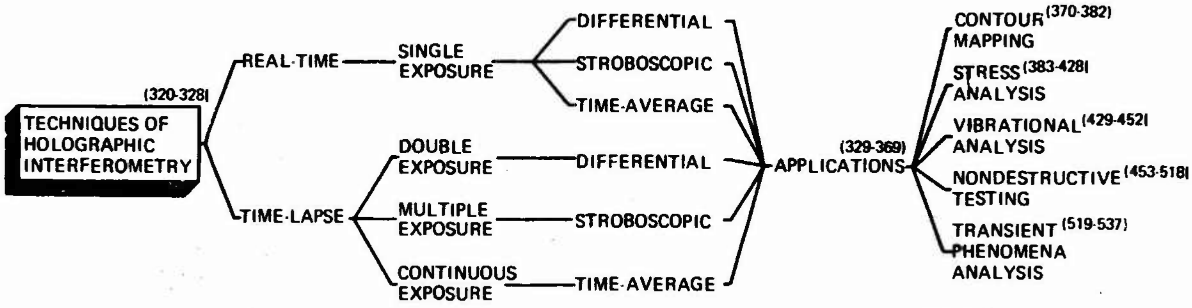
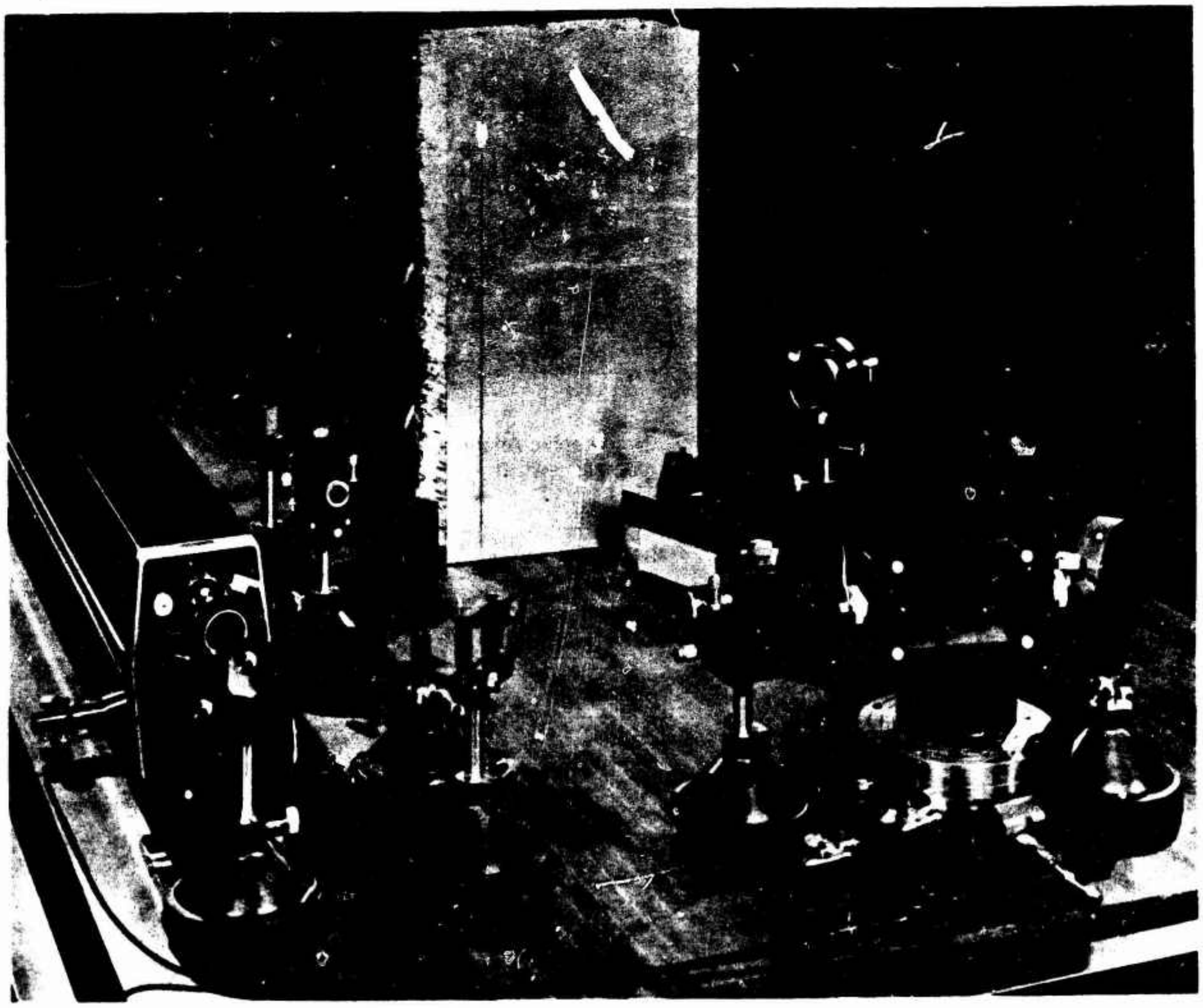


Figure 27. Techniques and Applications of Holographic Interferometry[17,74-80]



Amazing accuracy, sensitivity to surface displacements of as little as 12 microinches, and versatility combine to make a laboratory-model holographic interferometer a powerful new tool for researchers, designers, and quality-assurance engineers in many fields. Among its established capabilities are nondestructive detection of subsurface discontinuities in many kinds of materials, vibration analysis, contour mapping, and displacement measurements.

Figure 28. Commercial Laboratory-Model Holographic Interferometer
19-066-198/AMC-71

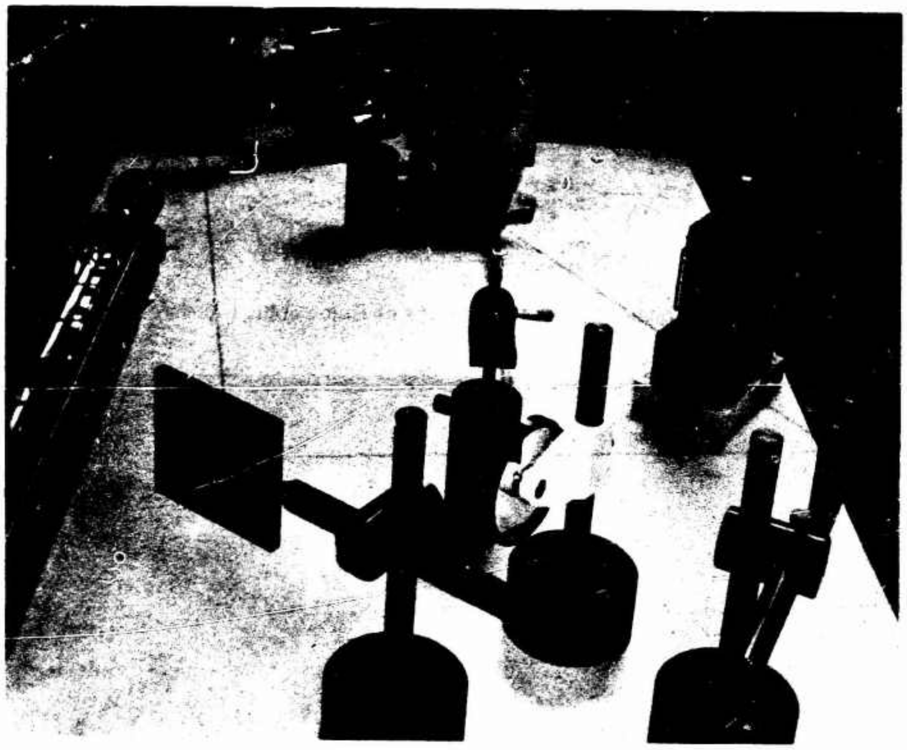


Figure 29. Holographic Analysis Equipment
19-066-375/AMC-71

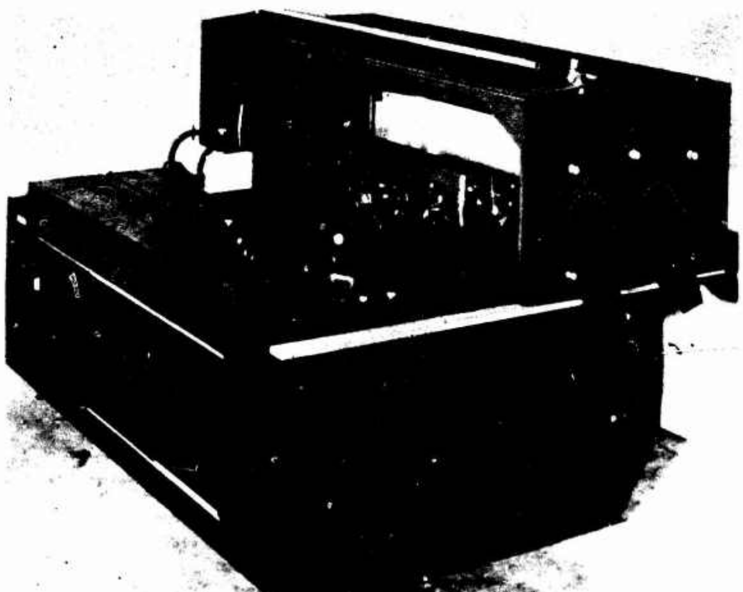
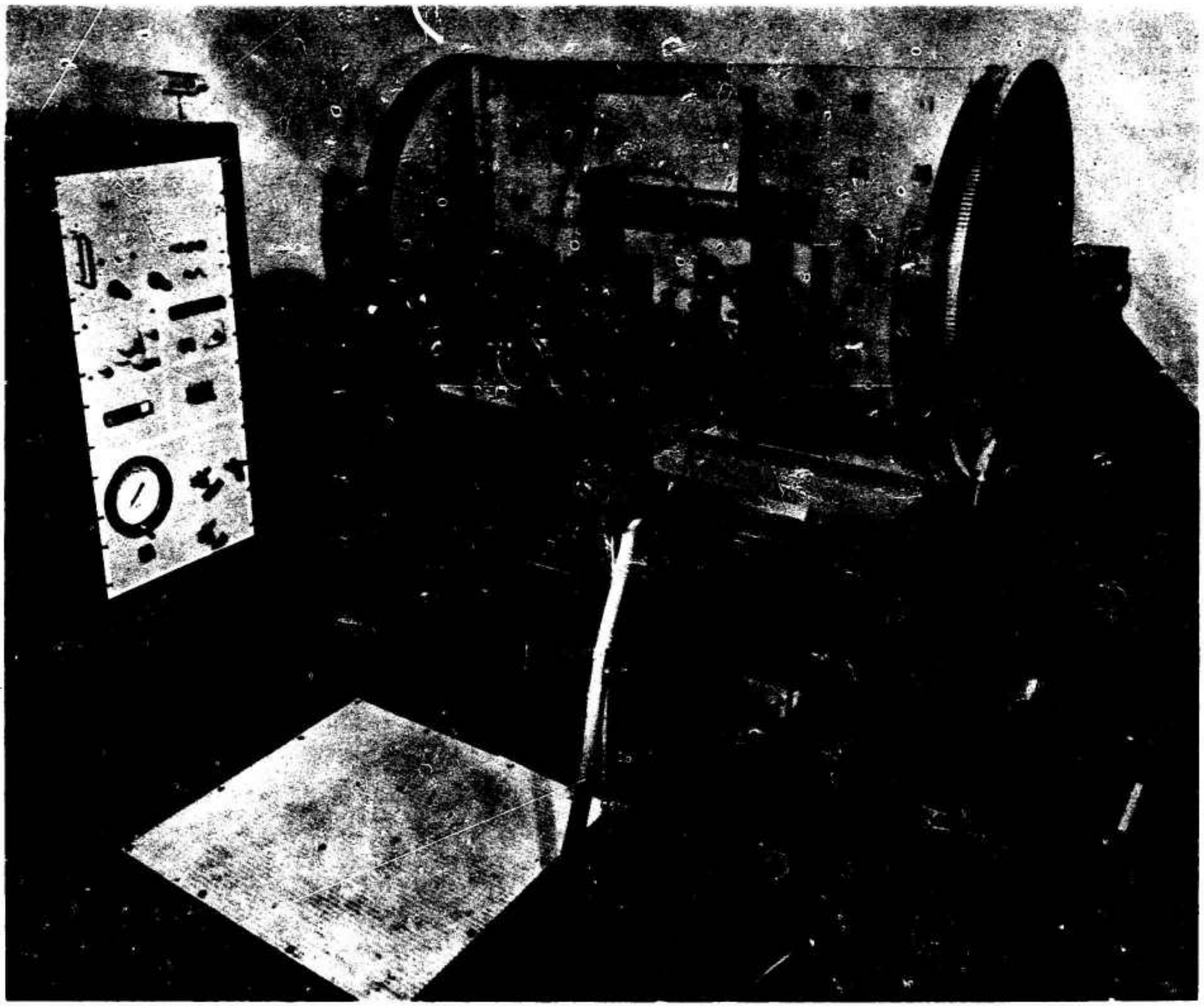


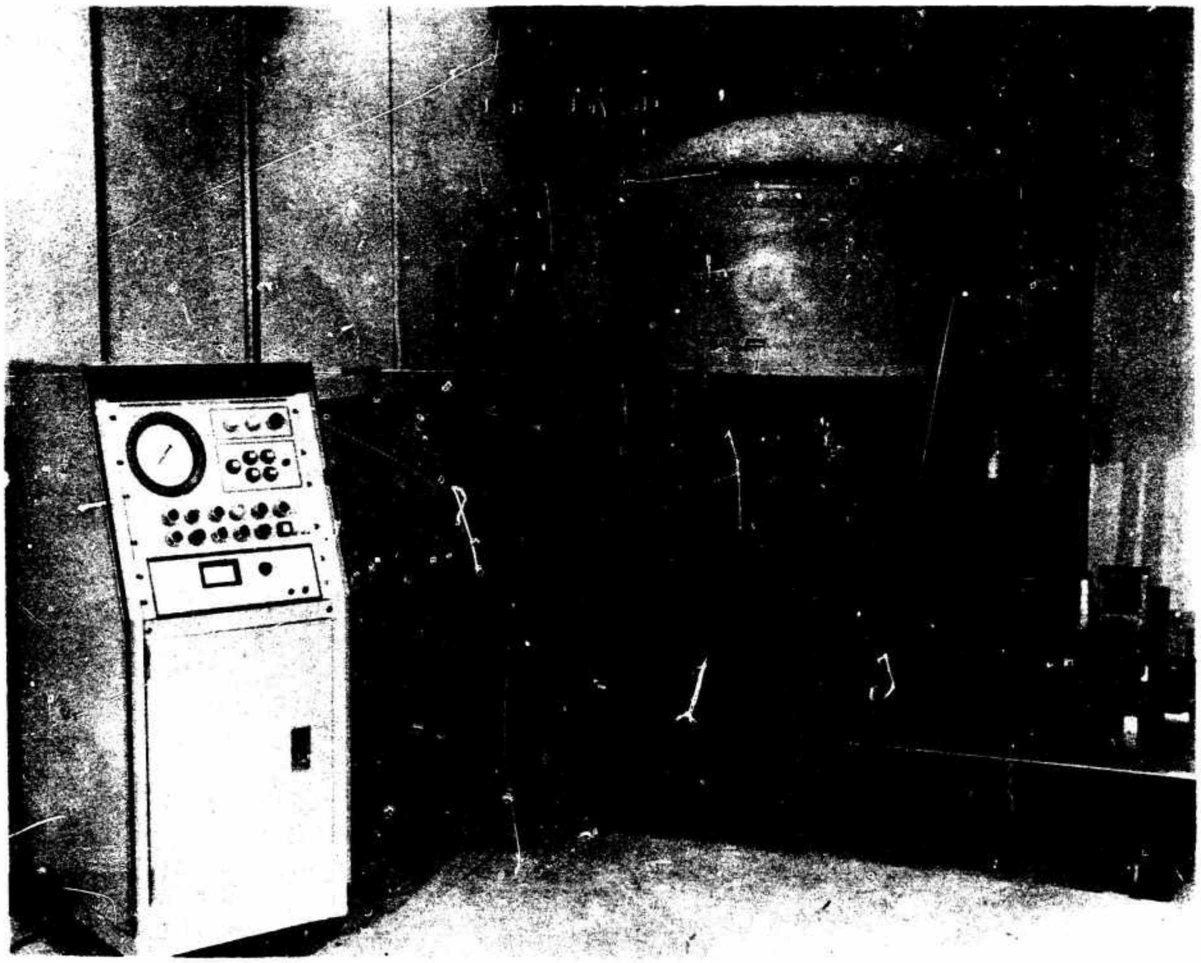
Figure 30. Commercial Holographic Transducer Analyzer
19-066-186/AMC-71

A powerful tool for design and quality control of acoustic transducers, the GCO series 2000 Holographic Transducer Analyzer can be used to: display head-flexure modes, measure displacement over entire vibrating surface, identify resonant frequencies; locate separations in rubber-to-metal bonds, reveal subsurface defects in rubber gaskets, etc.



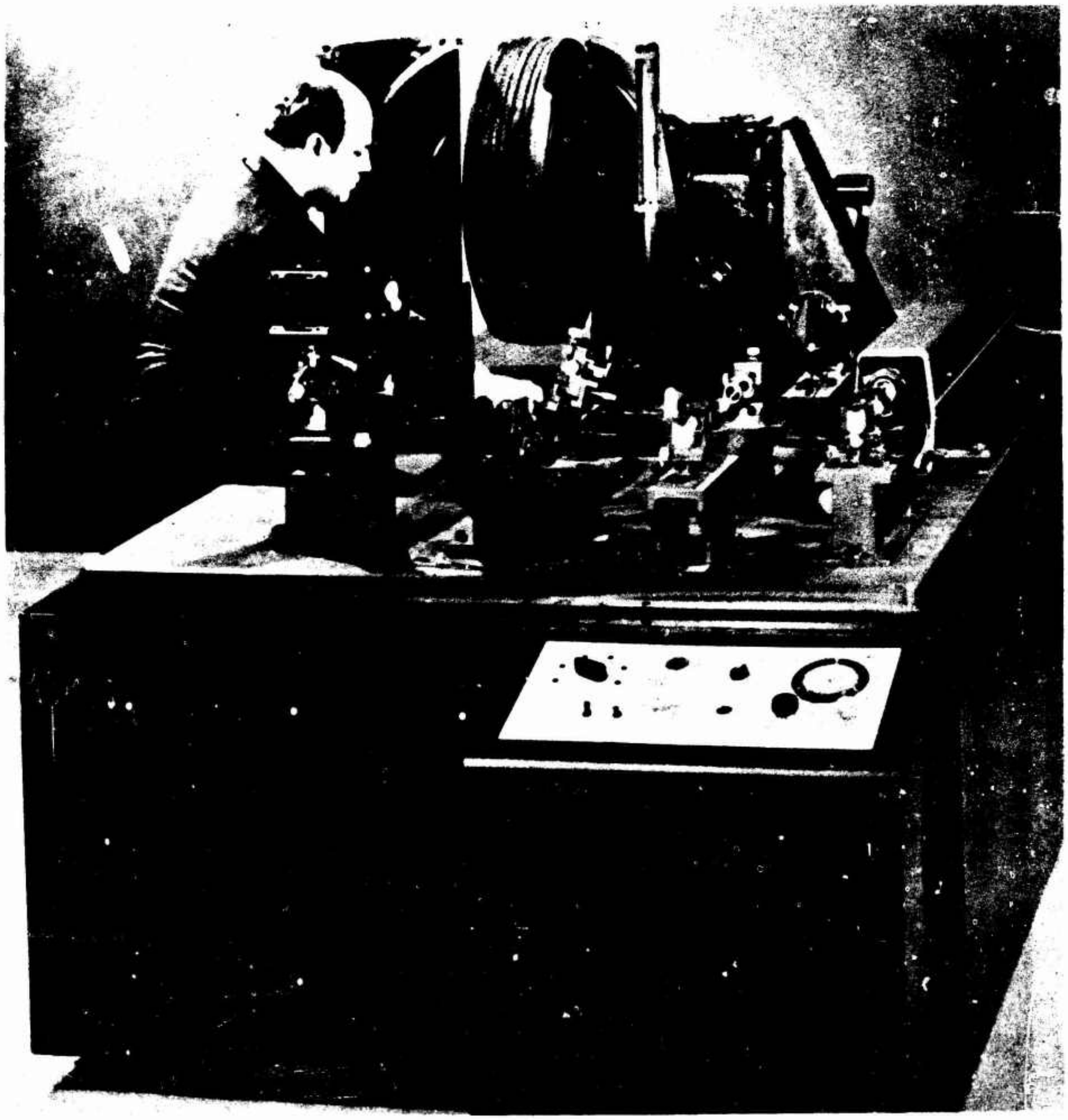
Subsurface defects in honeycomb-sandwich structures are located with accuracy, reliability, and speed on this holographic analyzer. This model can test a contoured or flat panel up to 25 square feet in projected surface area in 40 minutes or less. A choice of thermal, vibration, pressure, or vacuum stressing may be applied. Both the real-time view and the corresponding permanent record are interpreted directly, with the size, shape, and location of the defect clearly superimposed in the natural position on the image of the test panel.

Figure 31. Commercial Holographic Honeycomb Panel Analyzer
19-066-189/AMC-71



The GCO Model PT-12 Holographic Tire Analyzer, shown above, employs the principle of time-lapse, double-exposure, holographic interferometry. The analyzer is capable of inspecting tires ranging in size from a minimum of 12 inches rim diameter to a maximum of 45 inches outside diameter at a rate of better than 12 tires per hour when auxiliary semi-automatic options are employed. The inspection procedure consists of producing a double-exposure hologram of each quadrant of the inner walls of the tire undergoing examination. The first exposure is made of the tire in its initial state of stress - the tire having been mechanically pre-spread at the beads - and the second exposure is made following the application of a slight vacuum. Defect anomalies are manifested by minute changes in the inner-wall topography occurring as a result of the pressure differential existing between the unvented tire defects and the evacuated tire testing chamber.

Figure 32. Commercial Holographic Tire Analyzer



The GCO Model 4158 Holographic Tire Analyzer can analyze pneumatic tires of up to 33 inches in diameter and up to 12 inches wide. The analyzer consists of a pneumatic, servo-controlled, vibration isolation system and surface plate; a tire holding and stressing fixture; and a holographic interferometer including a helium-neon laser. This model can conveniently and completely analyze three or four tires an hour for all subsurface separations and construction features. The tire holder indexes to four equal positions, and each hologram analyzes the tread and both sidewalls of the tire simultaneously.

Figure 33. Commercial Holographic Tire Analyzer

Figure 34. HNDT-Passenger Car Tire
19-066-193/AMC-71

Both sidewalls and the treads are simultaneously analyzed for all hidden separations and structural features by the GCO Model 4158 Holographic NDT tire analyzer. This holographic interferogram of an 8.25 x 14, four-ply tire dramatically reveals a shoulder separation between the liner and the first ply plus a separation between the first and second plies in the tread region. These flaws were brought out by natural creep, after inflation to 50 psi, and double-exposure holographic (three-dimensional) interferometry.

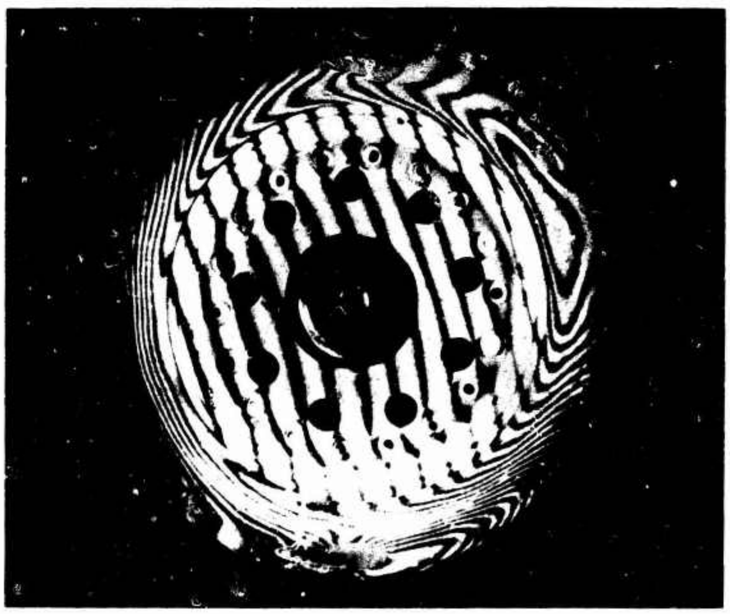
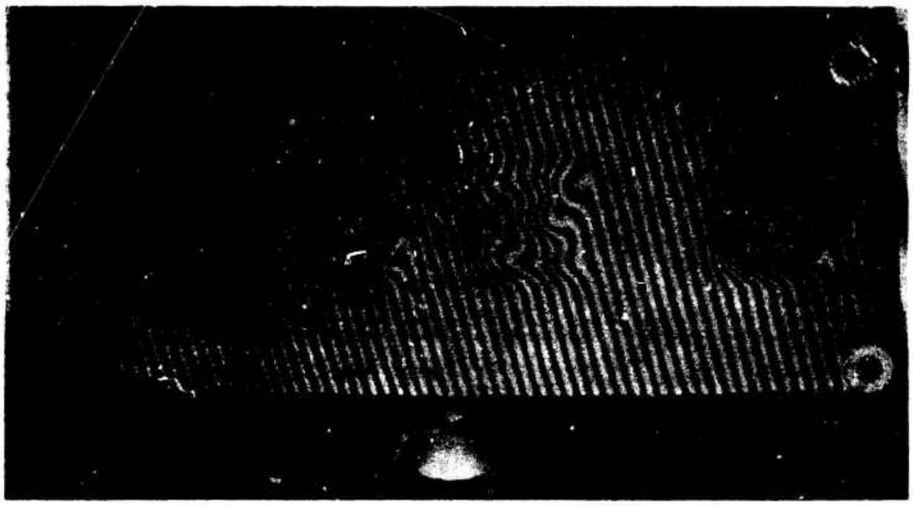


Figure 35. HNDT-Aircraft Tire
19-066-197/AMC-71

Vacuum/memory stressing and double-exposure holographic interferometry were used for nondestructive testing of this 25 x 6.75/18-PR aircraft tire. Separations were (clockwise from top) at first-wire turnup (1/2-inch deep), sidewall (0.15-inch deep), and second-wire turnup (0.4- to 0.5-inch deep).

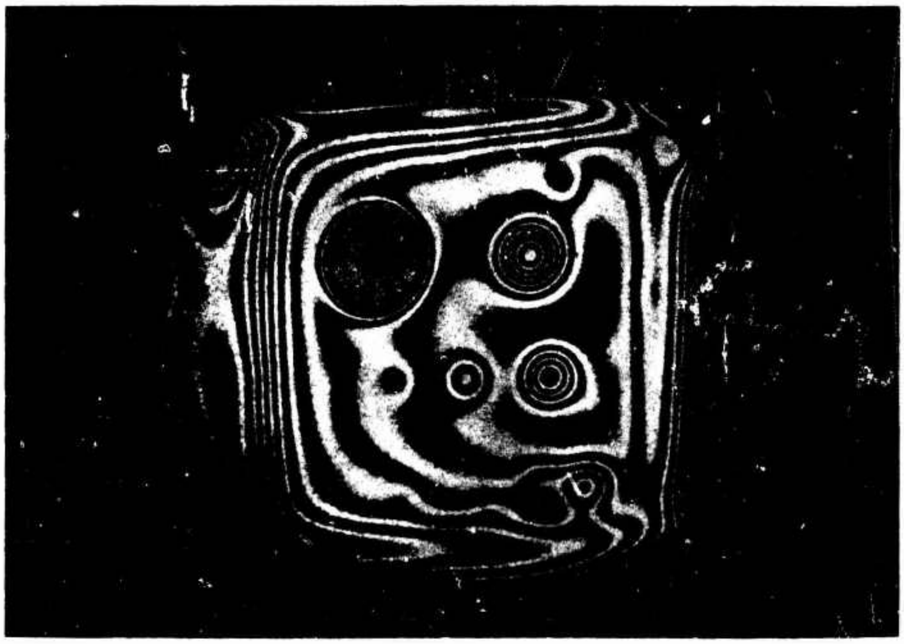
Double exposure holographic interferometry and mild thermal stressing clearly and reliably revealed unbonds between a steel cylinder and diffusion-bonded aluminum cladding.

Figure 36. HNDT-Steel Cylinder with Diffusion-Bonded Cladding



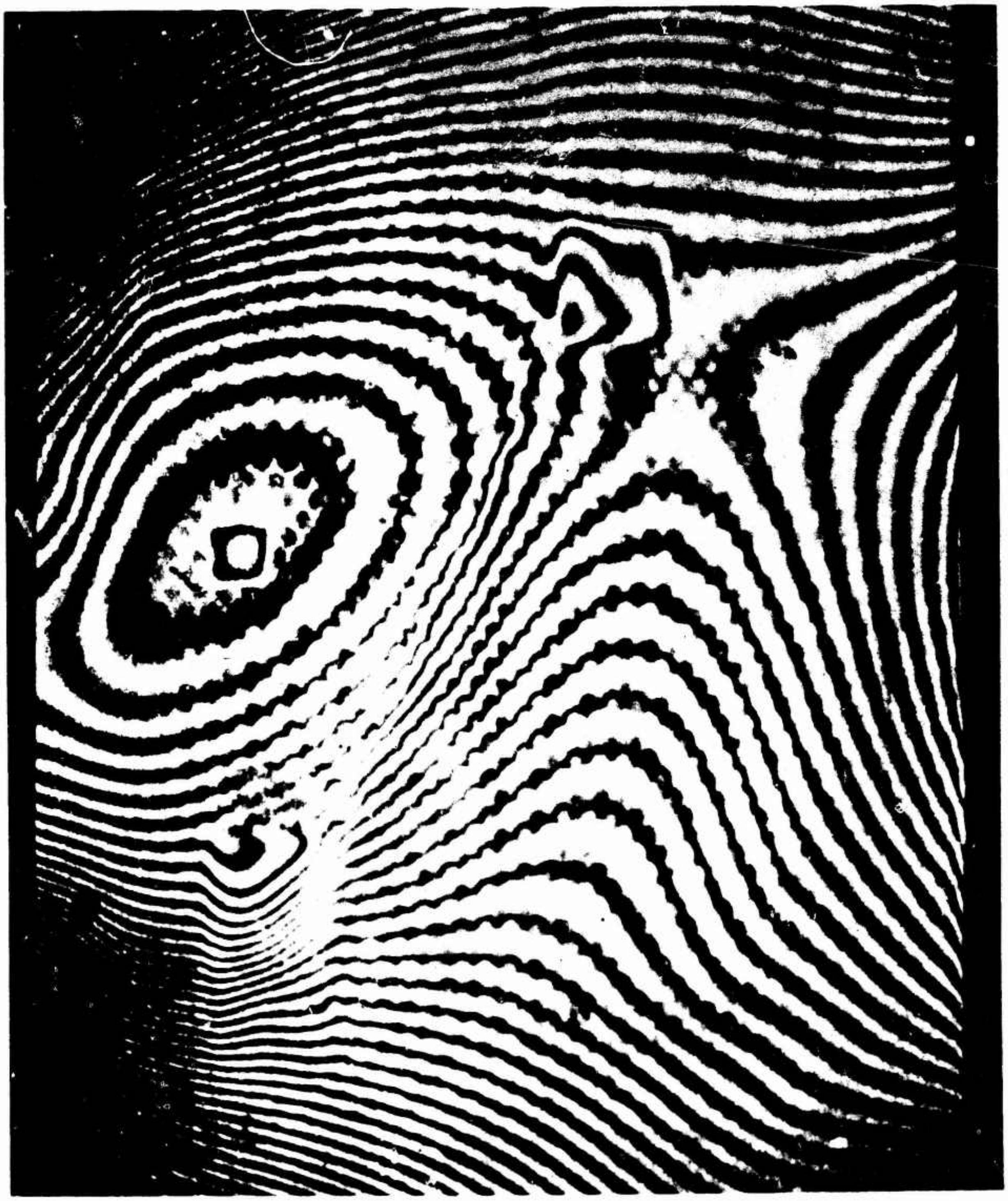
All four programmed flaws (each 2 inches square) in this honeycomb-sandwich panel were sharply outlined by vacuum stressing and double-exposure holography with a pressure reduction between exposures. The quarter-inch aluminum honeycomb was bonded between boron-epoxy skins (with 0.04-inch-thick titanium doubler between the core and the far skin). The second defect from the right was caused by crushed core. The others were missing adhesive (from left to right): between far skin and doubler, between doubler and core, and between core and near (10-ply) skin.

Figure 37. HNDT-Honeycomb-Sandwich Panel
19-066-19?/AMC-71



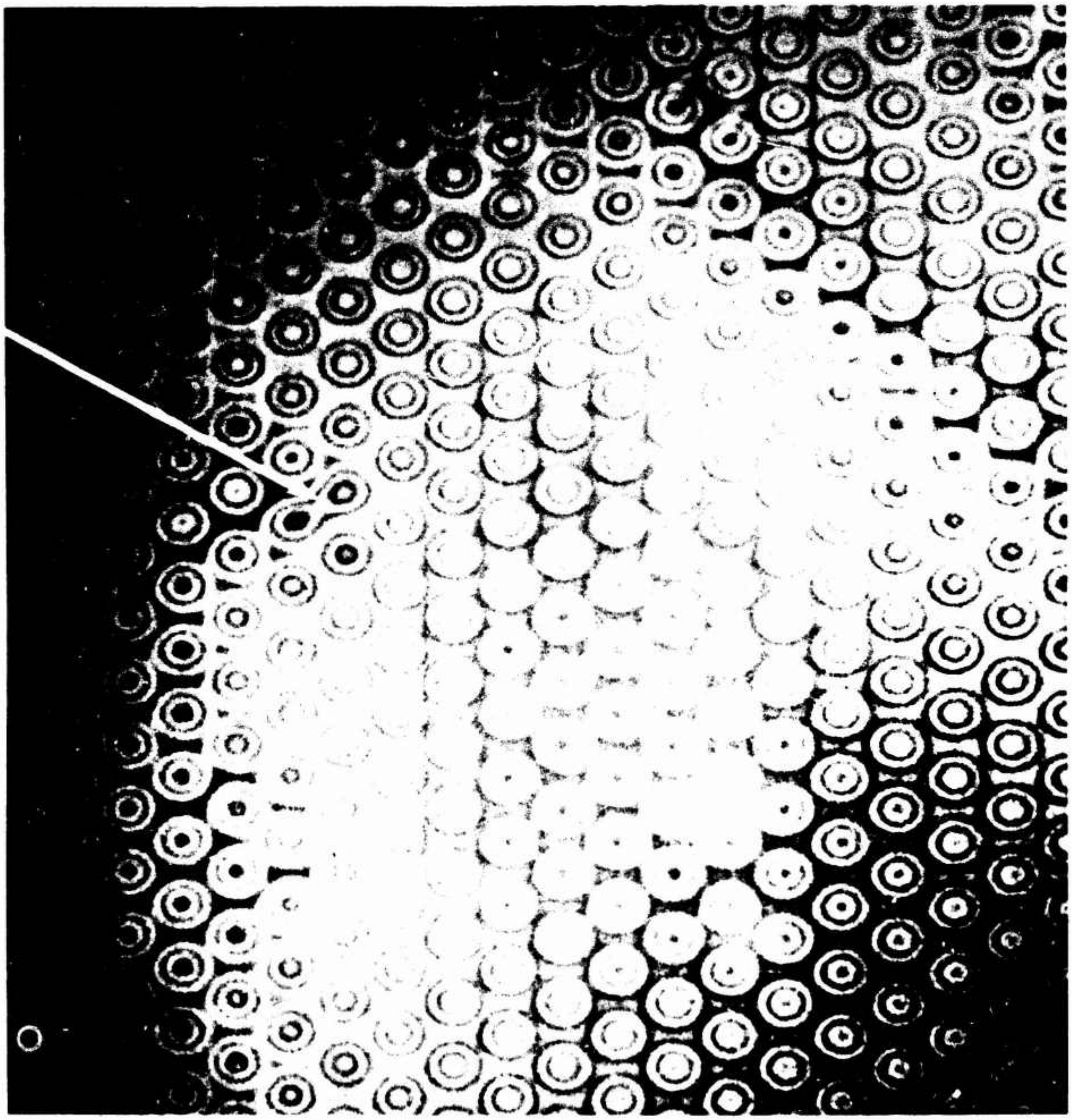
Debonds as small as 1/4-inch in diameter were readily detected by double-exposure hol-graphy of a rubber-to-aluminum laminate. A uniform vacuum was applied to the test panel, and the rubber continued to "creep" it was returned to atmospheric pressure. The resulting differential movement in each debond region was clearly revealed in the hologram as a series of concentric circles.

Figure 38. HNDT-Rubber-to-Aluminum Laminate
19-066-196/AMC-71



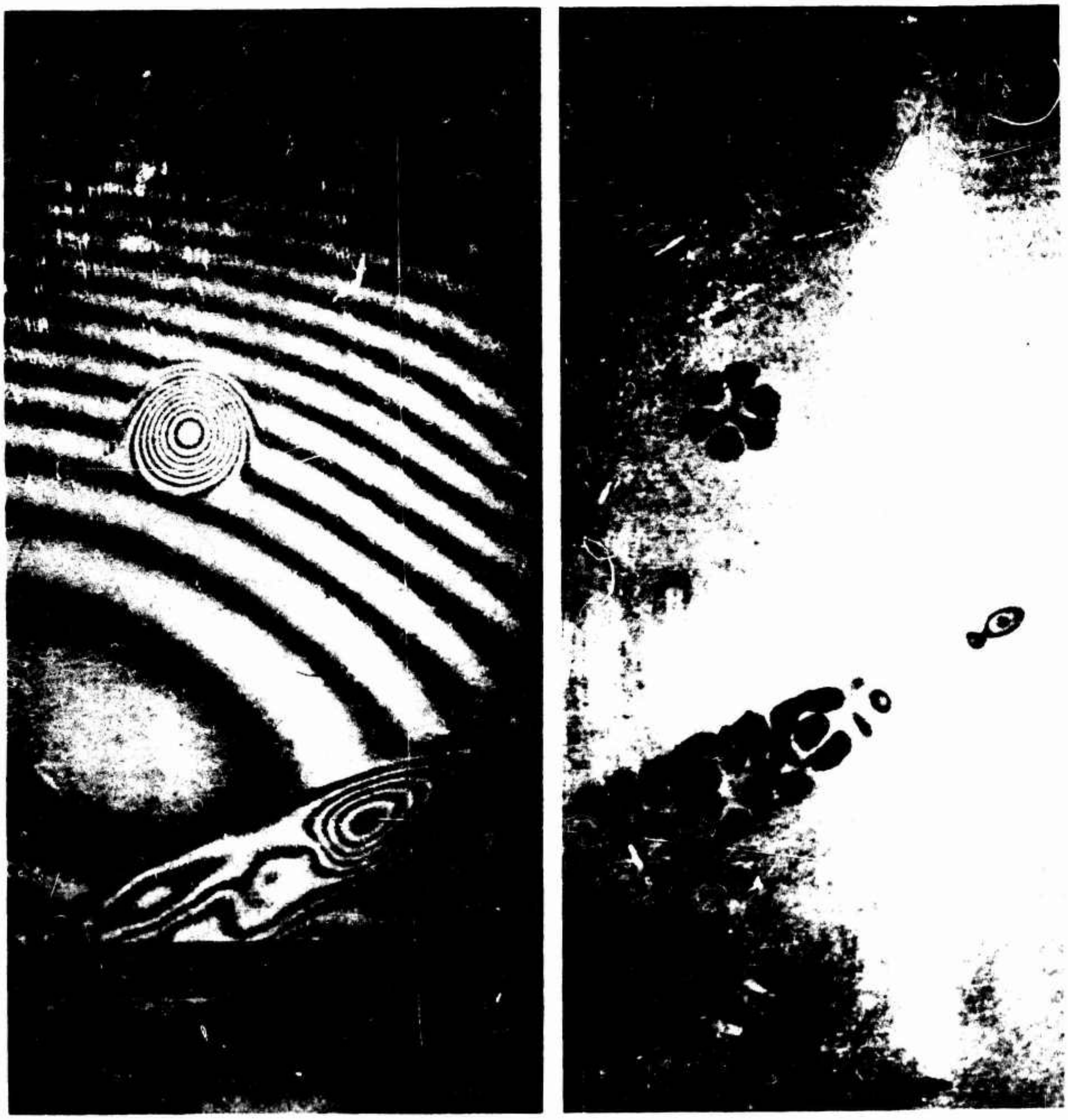
In a titanium honeycomb-sandwich panel, three debonds were detected by ermal stressing and real-time holographic interferometry.

Figure 39. HNDT-Titanium Honeycomb-Sandwich Panel
19-066-187/AMC-71



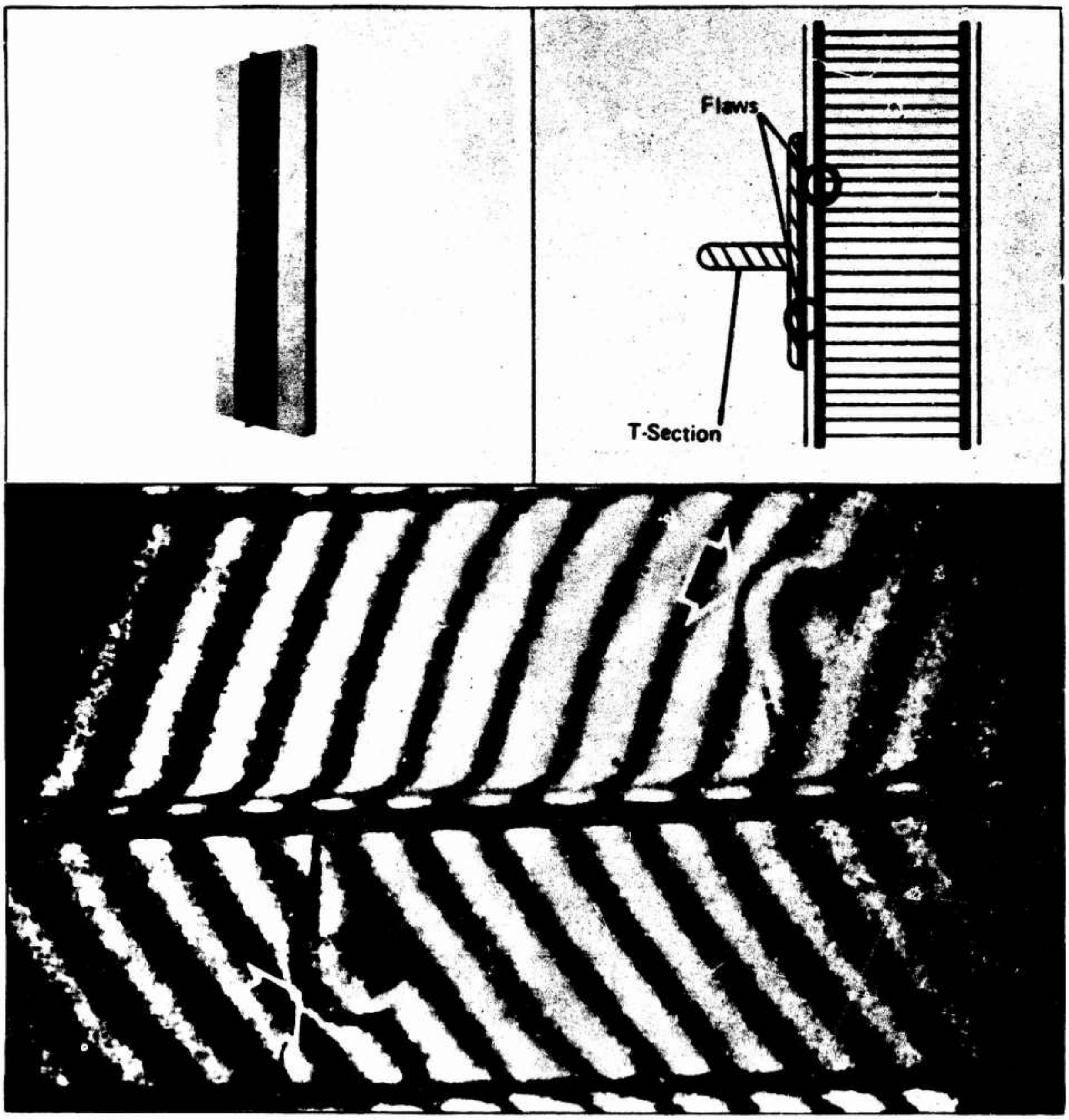
A figure-eight fringe anomaly around two cells below the center of this photograph reveals a single-cell-wall disbond between these cells in a diffusion-bonded, titanium, honeycomb-sandwich structure. This vivid delineation of individual honeycomb-core cells and the lone flaw was produced by real-time holographic interferometry and internal-pressure stressing of the panel (whose cells interconnect). The completely nondestructive test required only a few minutes on a GCO Model 3378 Holographic Sandwich-Structure Analyzer.

Figure 40. HNDT-Diffusion-Bonded Titanium Honeycomb-Sandwich Structure
19-066-191/AMC-71



An aluminum honeycomb-sandwich panel, with two debonds between skin and core, was nondestructively analyzed by holographic methods: vacuum stressing (300 mm of mercury) in real time (left) and acoustic-vibration stressing (31.5 kHz) and time-average holography (right).

Figure 41. HNDT-Aluminum Honeycomb-Sandwich Panel
19-066-195/AMC-71



An aluminum honeycomb-sandwich structure with a T-extrusion was mildly stressed by heat. This real-time holographic interferogram reveals two debonds under the T-section, one between the T-section and the skin, and the other between the skin and honeycomb core. Flaws such as these can be located even when there are no air gaps between the debonded parts.

Figure 42. HNDT-Aluminum Honeycomb Structure with a T-Extrusion
19-066-188/AMC-71

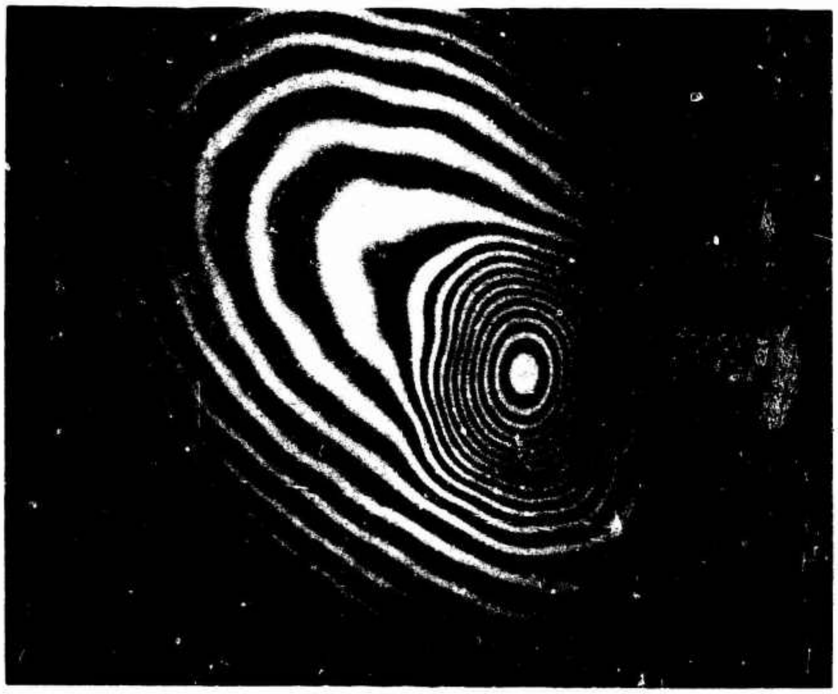


Figure 43. HNDT-Rubber-to-Metal Laminate: Holographic Interferometric Results of a 0.065-Inch Rubber-to-Metal Laminate with Programmed Voids Using a Heat Stressing Method.
19-066-376/AMC-71

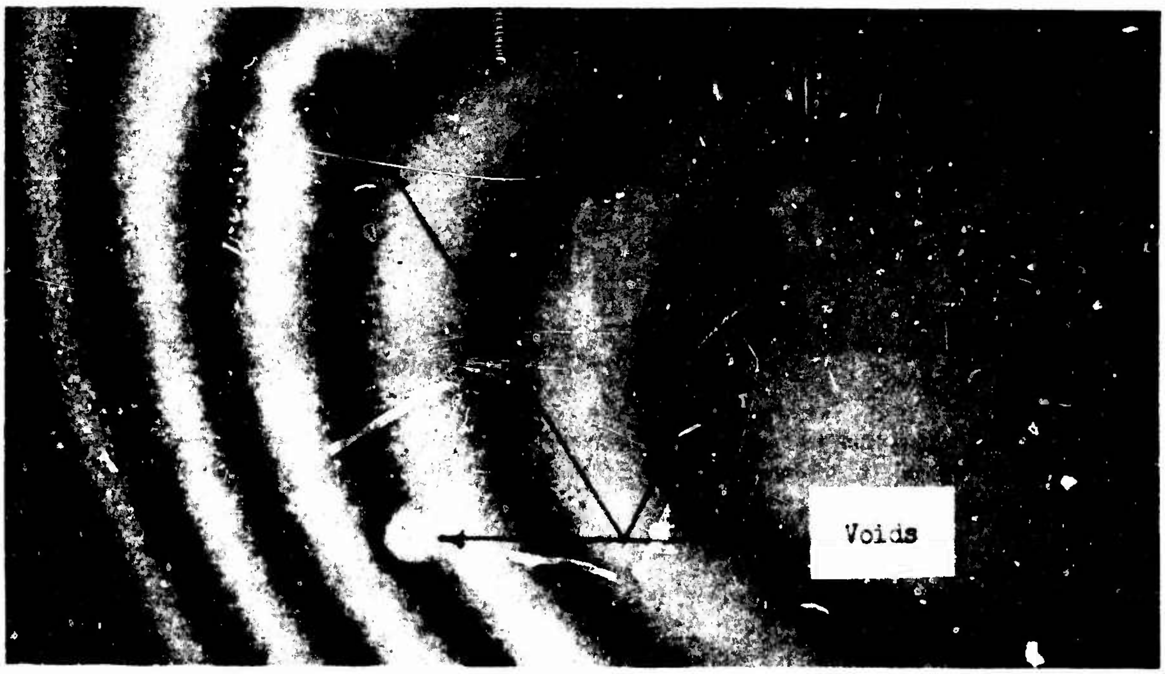


Figure 44. HNDT-Aluminum Honeycomb Panel: Fringe Perturbation Due to a 1-1/2 Inch Square Debond in a Honeycomb Panel.
19-066-373/AMC-71

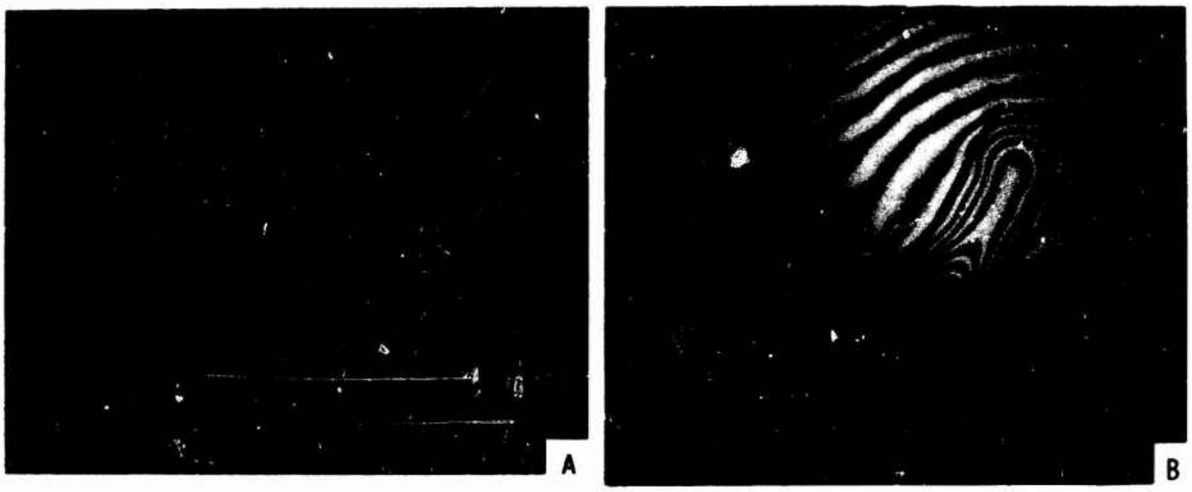


Figure 45. HNDT-Aluminum Honeycomb Panel: Holographic Interferometric Results Obtained Using Two Different Object-Loading Methods: (A) Vibration Technique (B) Vacuum Technique
19-066-465/AMC-71

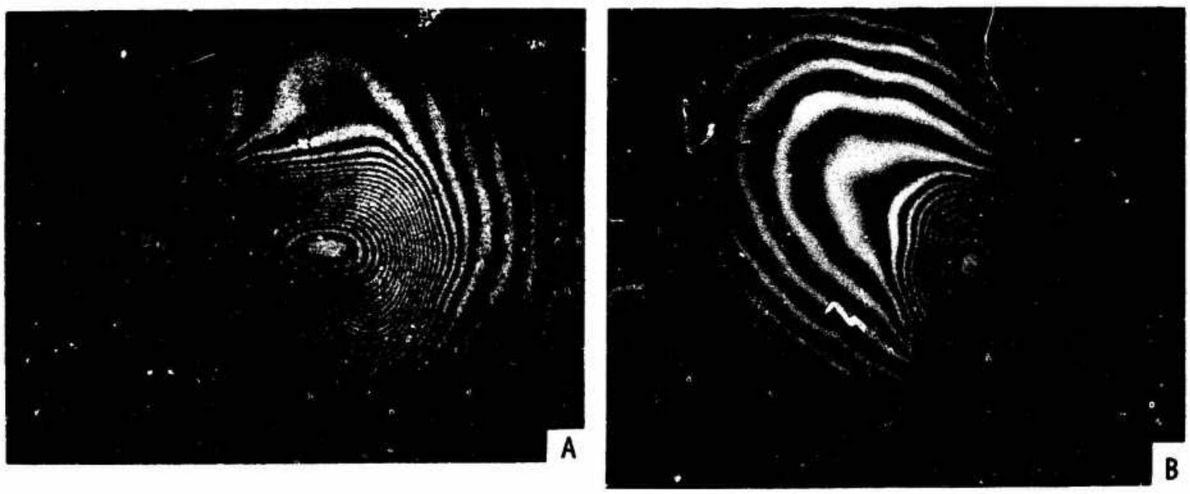


Figure 46. HNDT-Aluminum Honeycomb Panel: Holographic Interferometric Results Depicting Areas of Disbond Using Vacuum-Loading Technique: (A) 1.5-Inch Defect (B) 2-Inch Defect. A Higher Vacuum and Optical Magnification was Used to Produce Interferogram (A).
19-066-466/AMC-71

Figure 47. HNDT-Detection of Radial Microcracks in High-Strength Aircraft Structural Steel
19-066-378/AMC-71

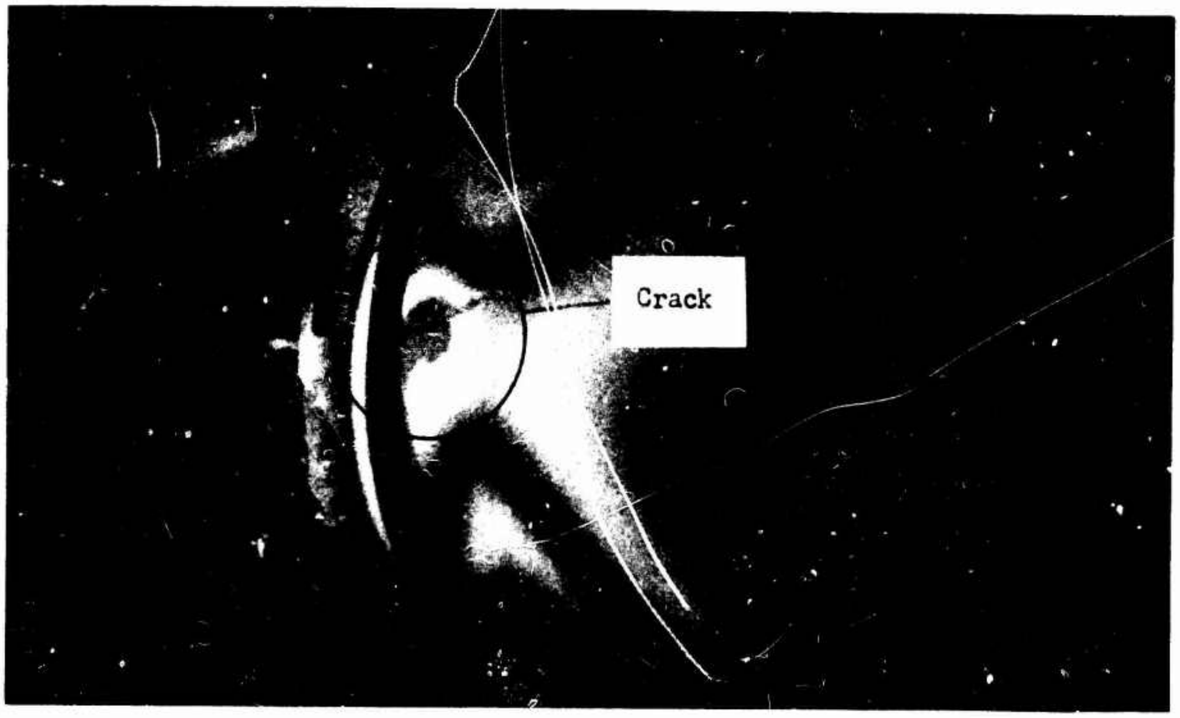


Figure 48. HNDT-Crack Detection in a 175MM Projectile: Interferometric Hologram Reconstruction of a 175MM Projectile with a Crack Near Fuse Plug.
19-066-377/AMC-71

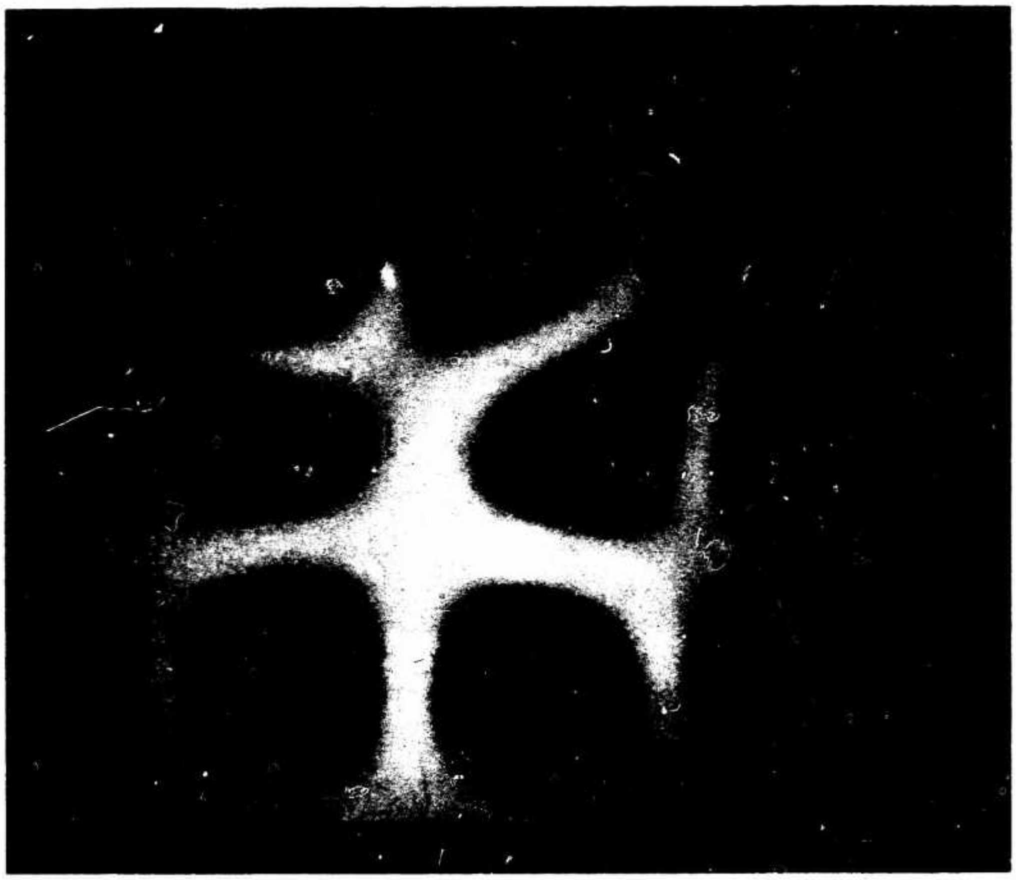
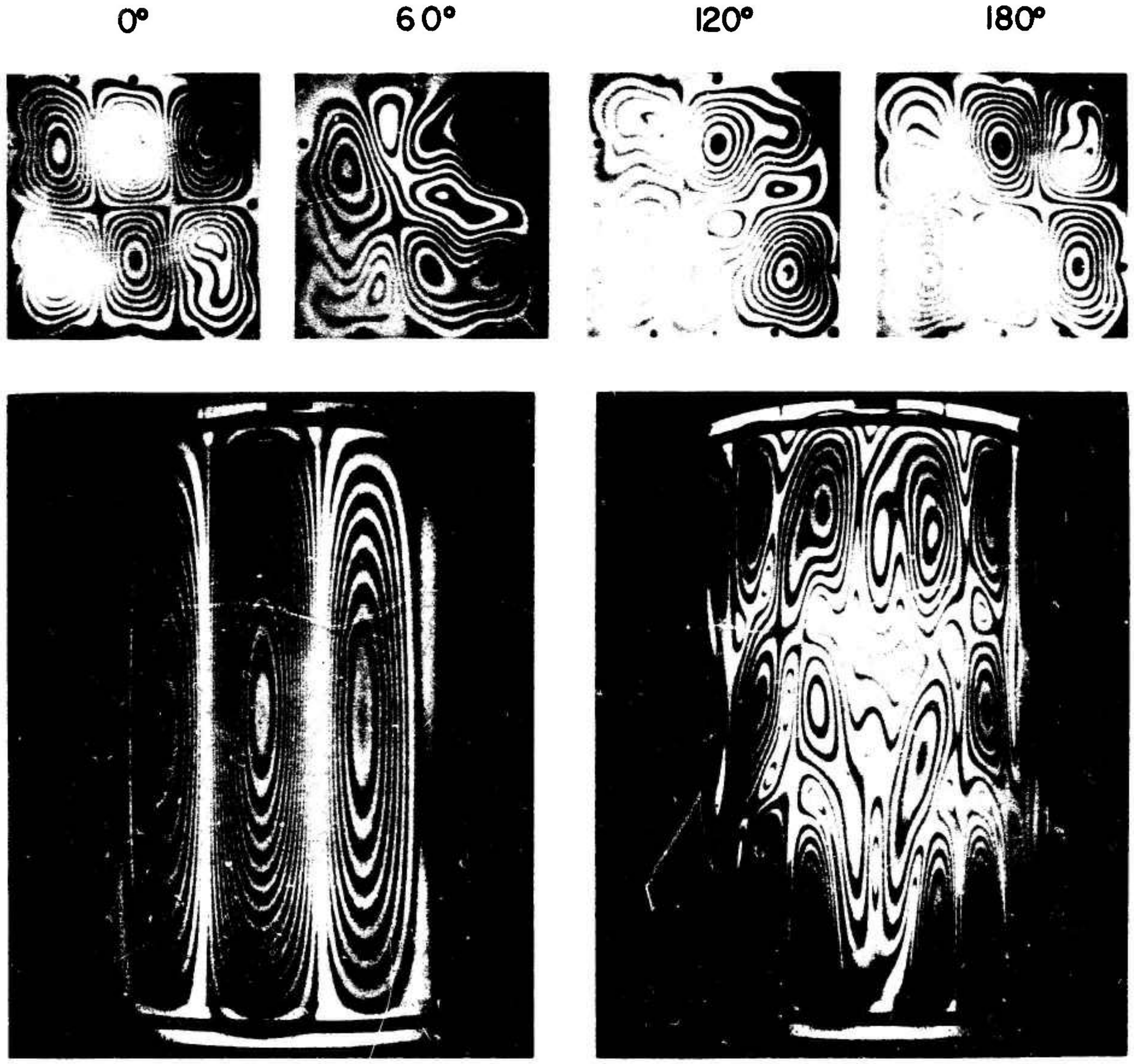


Figure 49. HNDT-Vibrational Analysis of a Metal Plate Vibrating at 1.775 KHZ
19-066-374/AMC-71

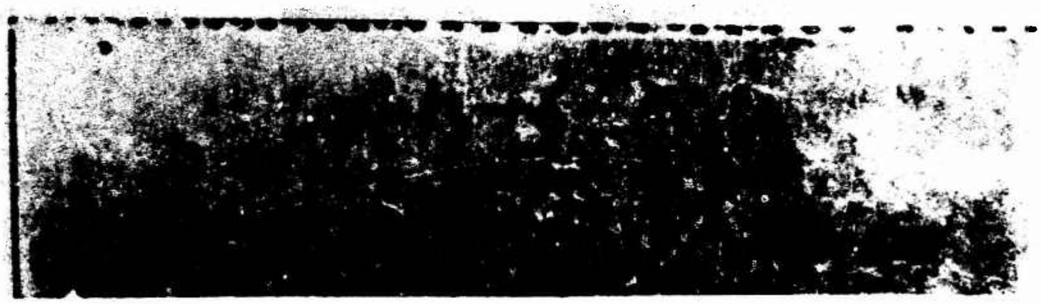


Examples of the use of holographic interferometry for vibration analysis: the upper row of photos of time-average holograms of a vibrating plate (1, 2 mode) show the effect of varying the phase of reference-wave phase shift. The lower pictures of time-average holograms of a vibrating cylinder show modal patterns that are highly symmetrical (left) and unsymmetrical (right).

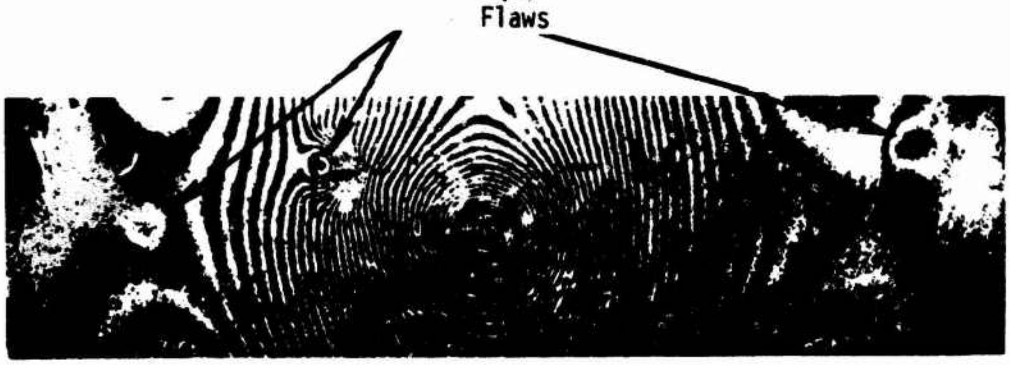
Figure 50. HNDT-Vibrational Analysis of a Metal Plate and Cylinder

19-066-185/AMC-71

(a)



(b)

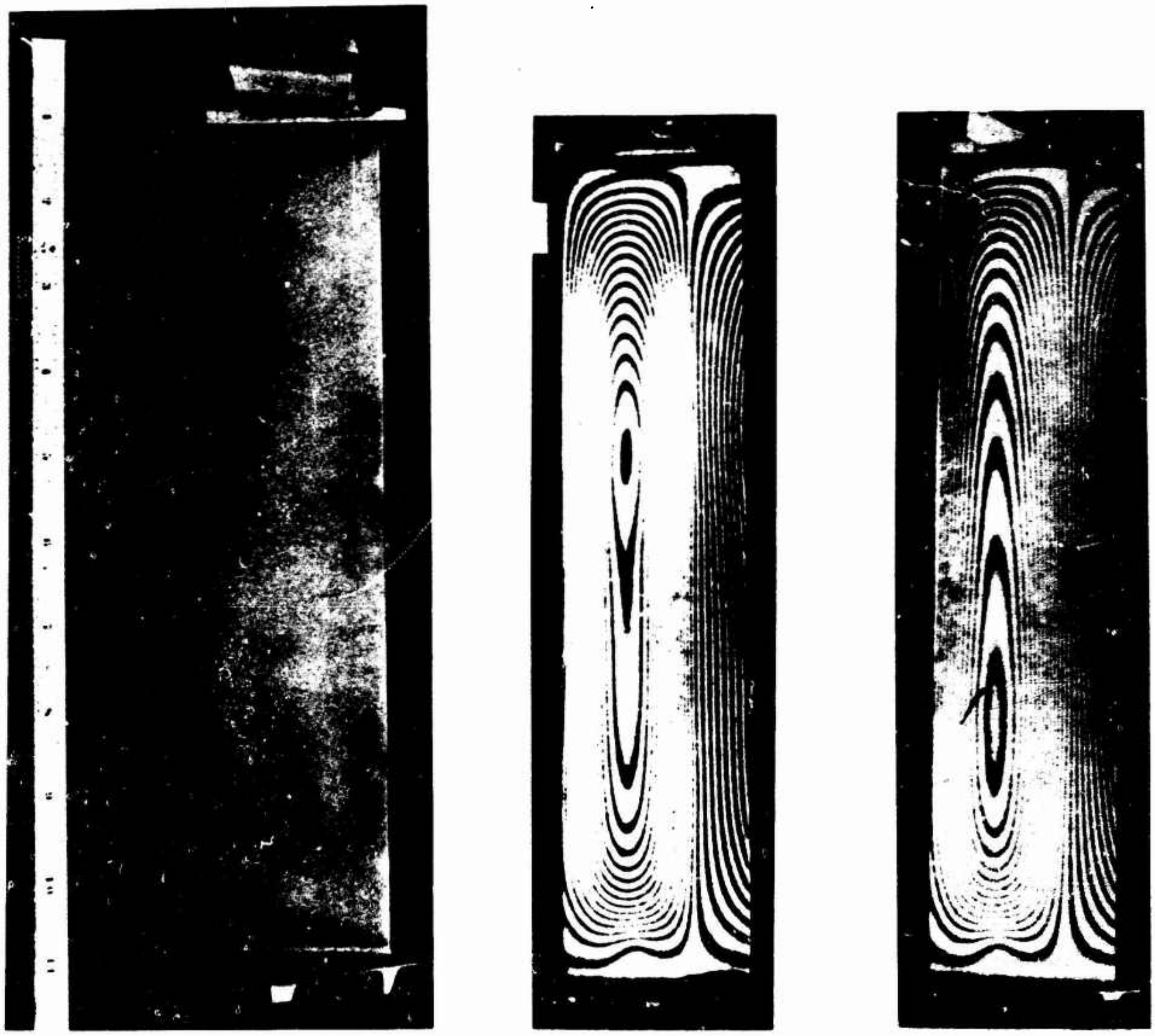


(c)

NDT of aluminum core, aluminum facesheets honeycomb panel. Flaws were introduced by removing the core from the front facesheets with a drill from the rear of the panel. A propagating transverse wave was caused to propagate by impacting the panel from the rear with a spherical pendulum.

(a) Top view of panel showing the core
(b) Front view of the honeycomb panel
(c) Holographic interferogram showing the defects in the panel.

Figure 51. HNDT-Aluminum Honeycomb Panel: Pulsed Holographic Nondestructive Testing
19-066-1256/AMC-71



a. Hollow Turbina Blade

b. Intarfarogram of an Acceptable Wall Thickness Turbina Blade. Peak Deflection 195 μinchas.

c. Interferogram of an Excessively Thick Wall Turbina Blade. Peak Deflection 175 μinches.

Nondestructive testing of hollow turbine blade using the technique of double exposure holographic interferometry. A change of 2 psi internal pressurization was introduced between exposures.

Figure 52. HNDT-Hollow Turbine Blade Seperation

19-066-1257/AMC-71

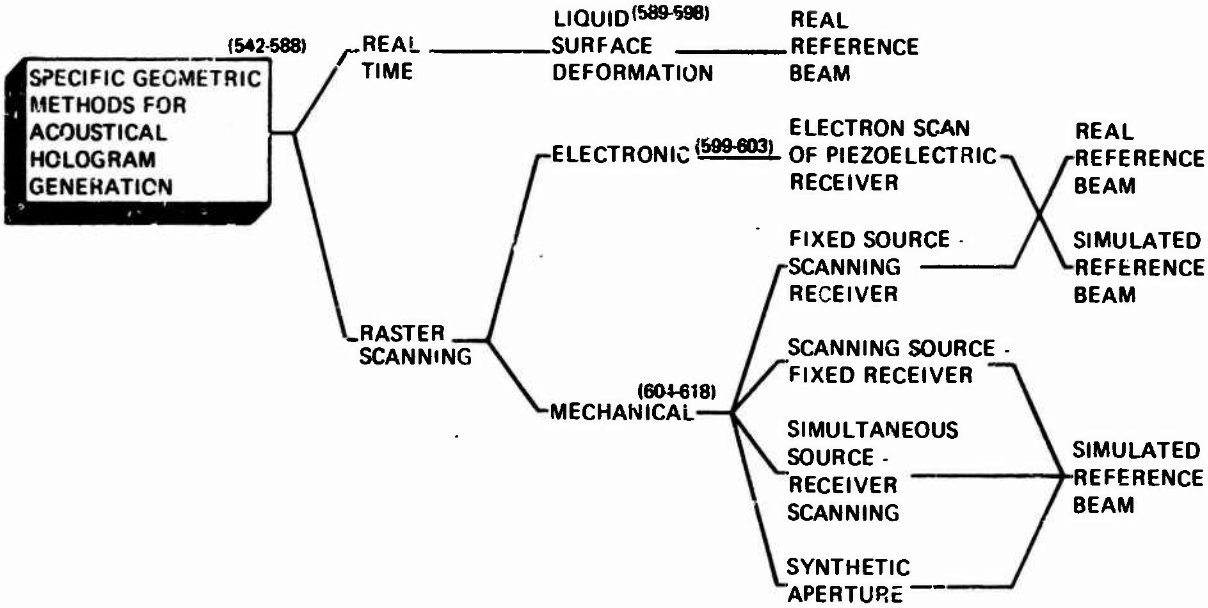


Figure 53. Specific Geometric Methods for Acoustical Hologram Generation

1. Ideal Geometry: $\frac{\sin \theta}{\lambda} = \frac{\sin \Theta}{\Lambda}$
2. $d = \frac{\Lambda}{2 \sin \Theta}$
3. $h = \frac{Ic}{2\pi^2 \gamma f^2 \sin^2 \Theta}$

   (γ = Surface Tension)
4. $h_o = \frac{4I}{g \rho C}$
5. $\sin \delta\theta = \pm \frac{\lambda}{\Lambda} \frac{\sin \Theta}{\cos \theta}$
6. Diffracted Light Amplitude:

   $A \propto \frac{h}{\lambda} \frac{1}{\cos\theta}$
7. Operating Criteria:

   f (MHz) $\sin \Theta \approx 0.233$

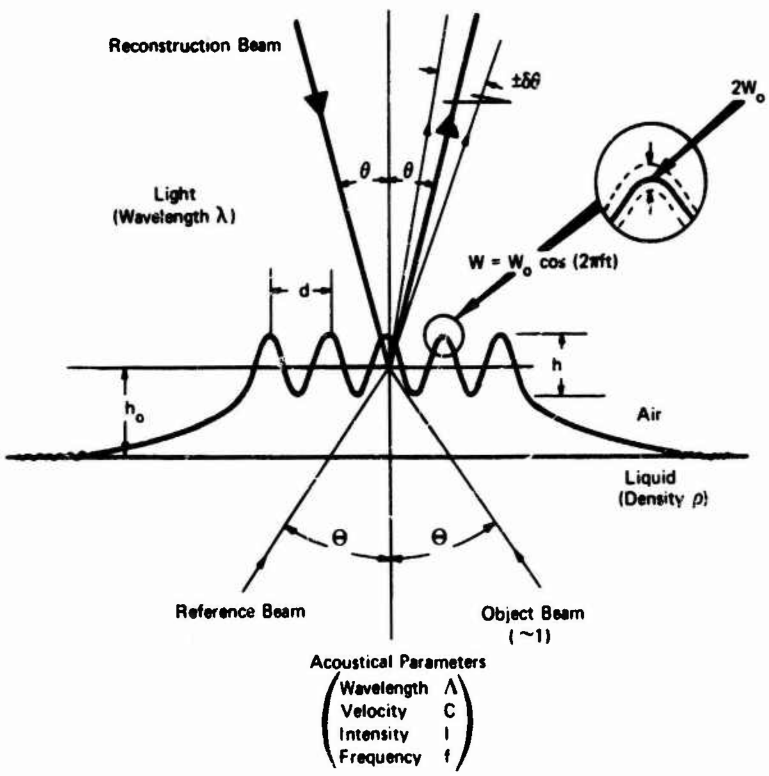


Figure 54. Liquid Surface Acoustical Holography. Simplified Surface Conditions and Equations

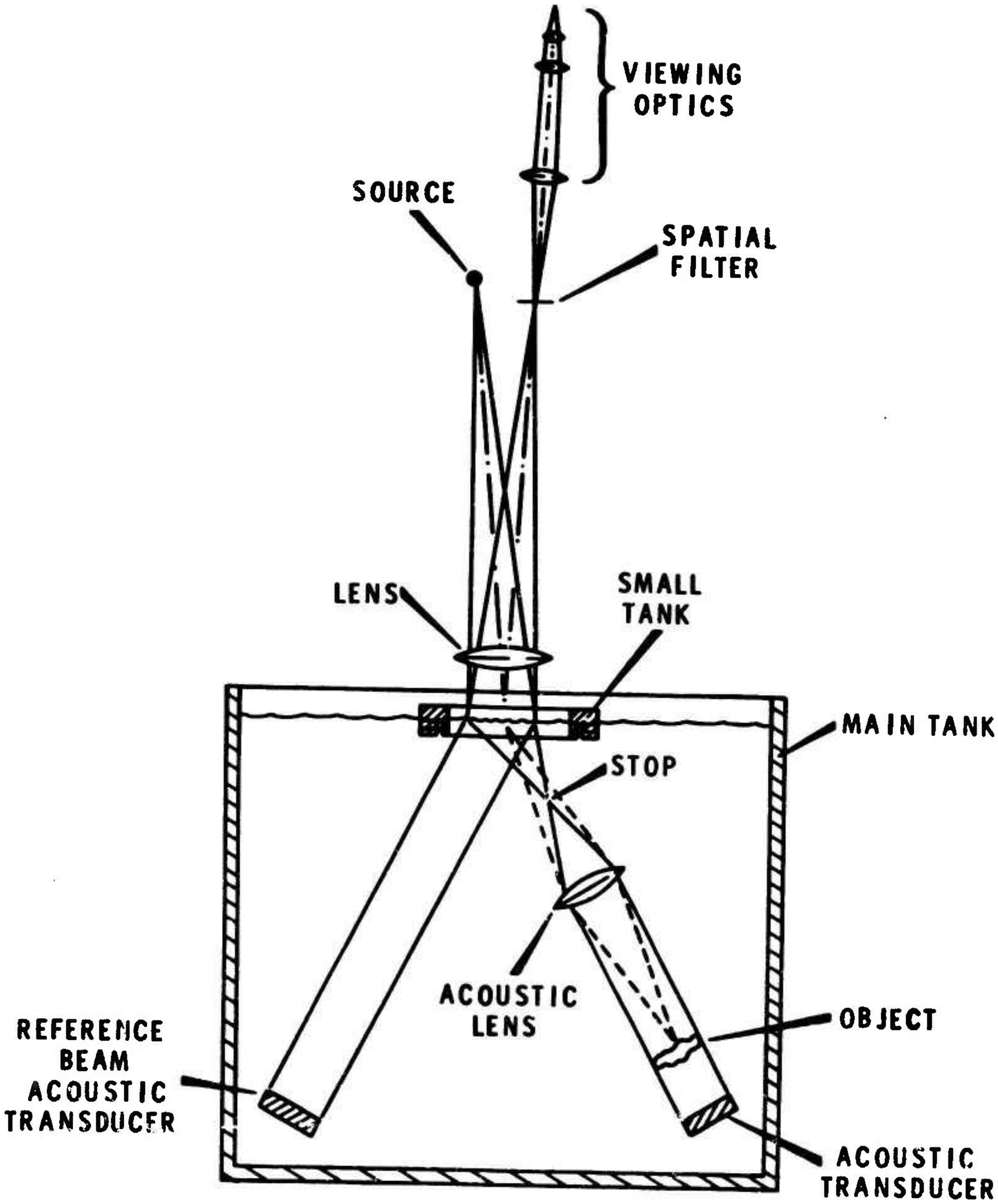


Figure 55. Acoustical Holography Basic Liquid Surface System

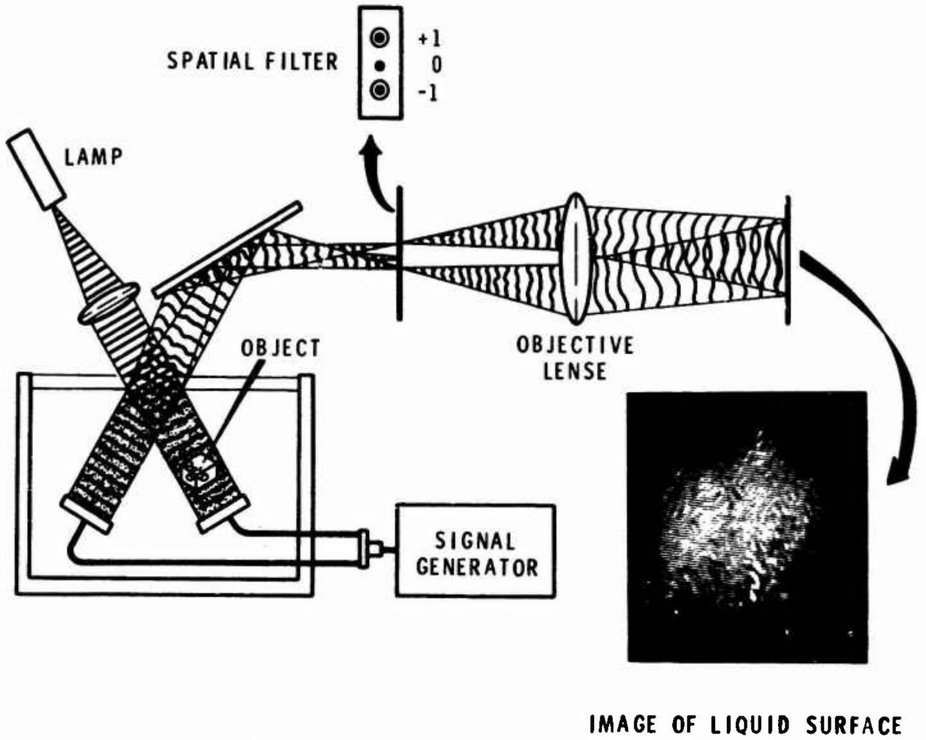


Figure 56. Method of Recording a Liquid Surface Hologram
19-066-520/AMC-71

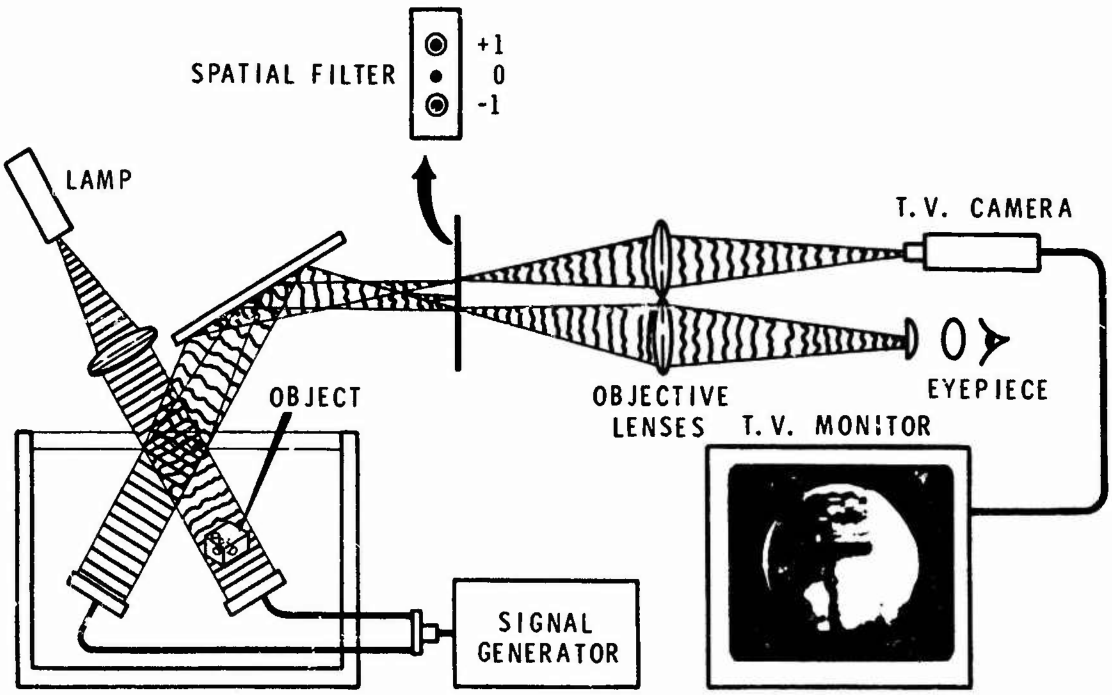


Figure 57. Acoustical Real-Time Holography Using a Liquid Surface
19-066-519/AMC-71

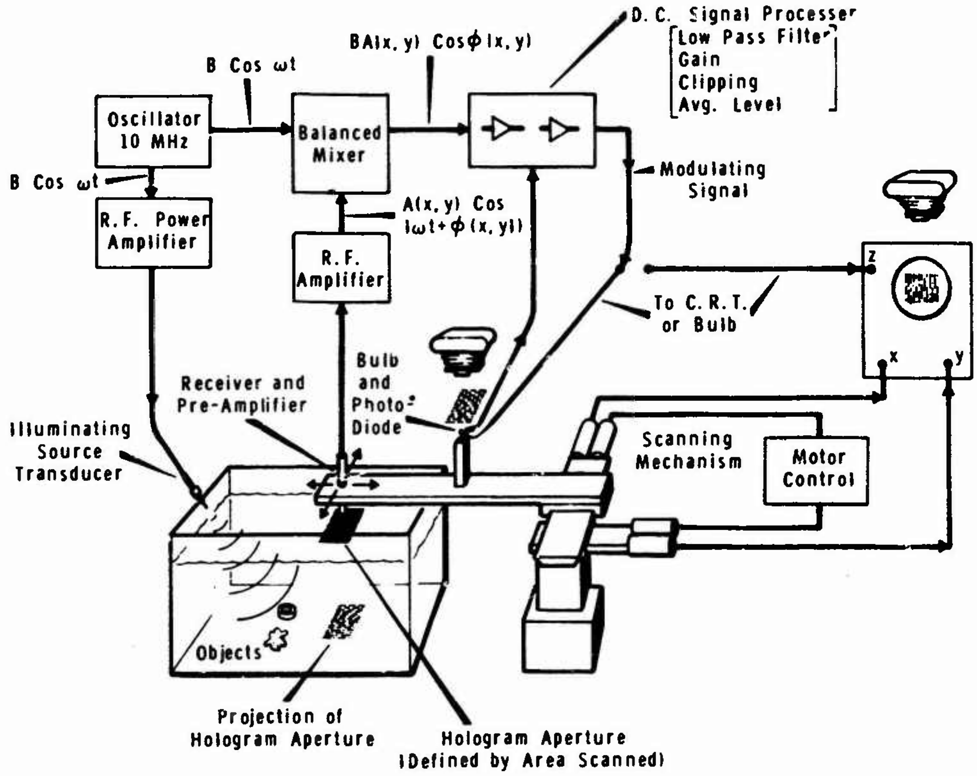


Figure 58. Acoustical Hologram Construction by Means of Mechanical Raster-Scanning Technique

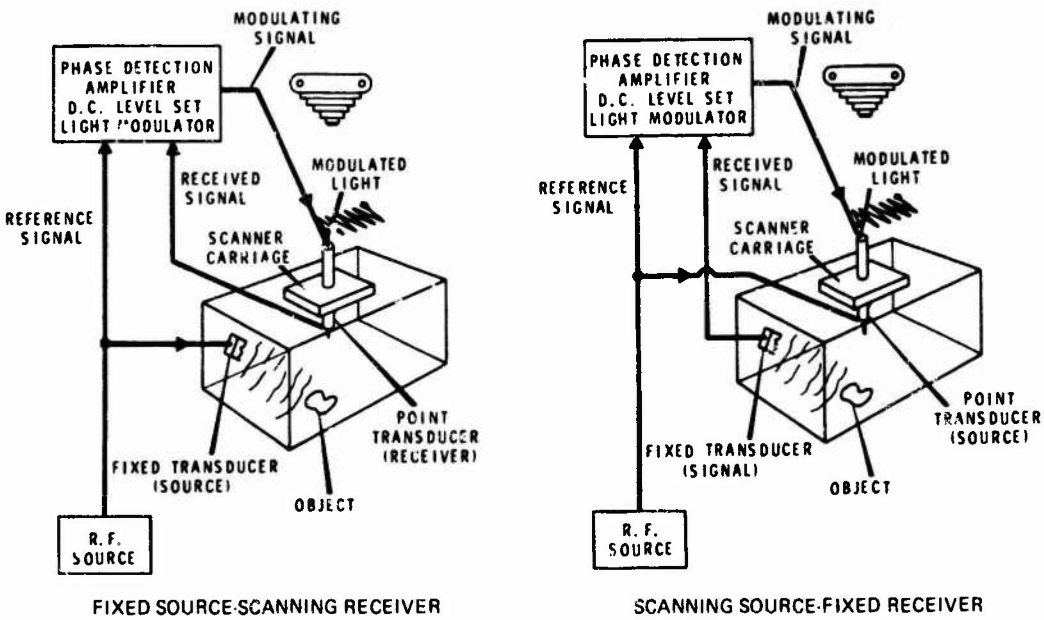
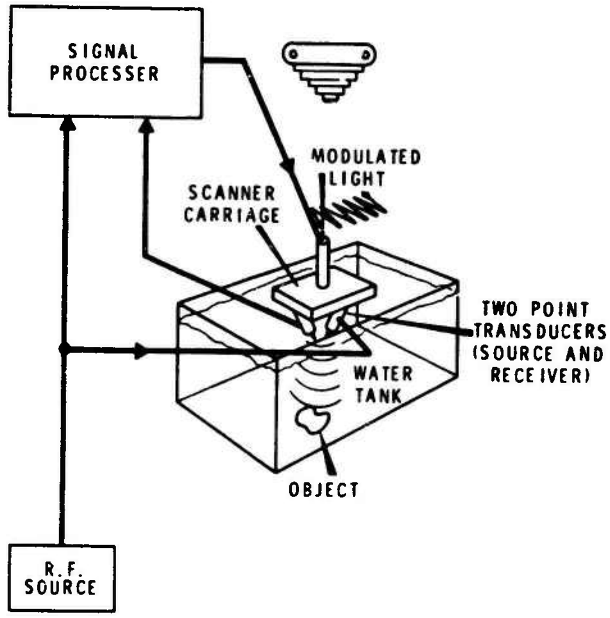
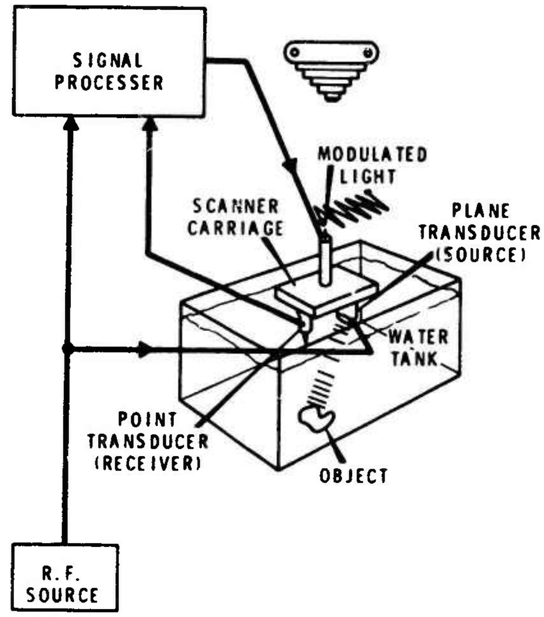


Figure 59. Acoustical Holography: Reciprocal Receiver or Source Scanning

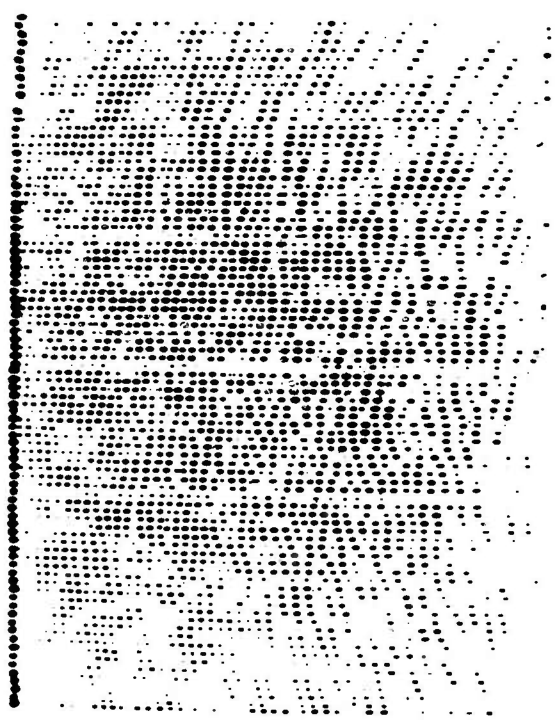


Coincident Source and Receiver



Plane Source Point Receiver

Figure 60. Acoustical Holography: Simultaneous Source-Receiver Scanning



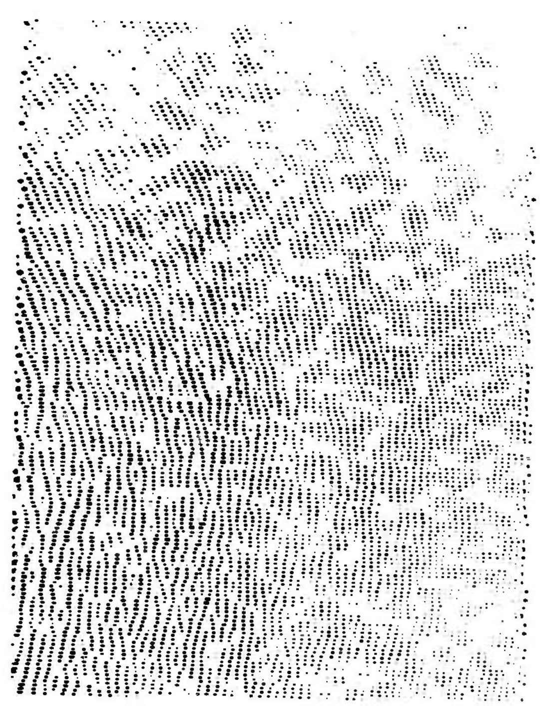
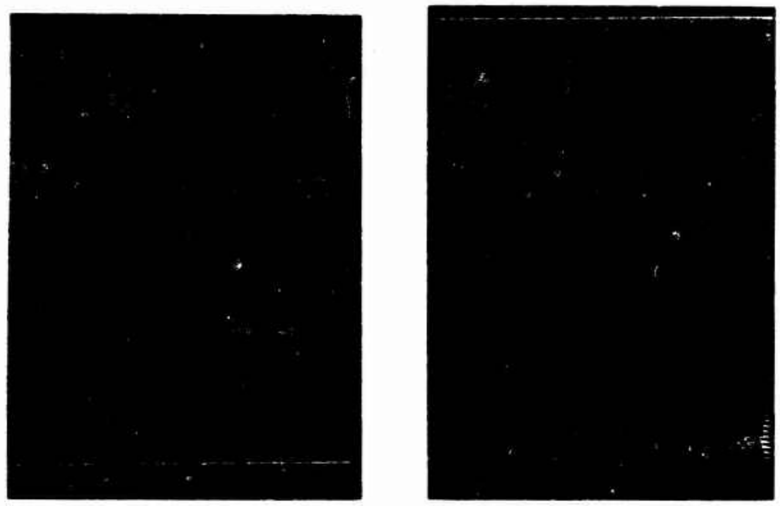


Figure 61. Examples of Scanned Acoustical Holograms



Normal (Receiver Scanning)

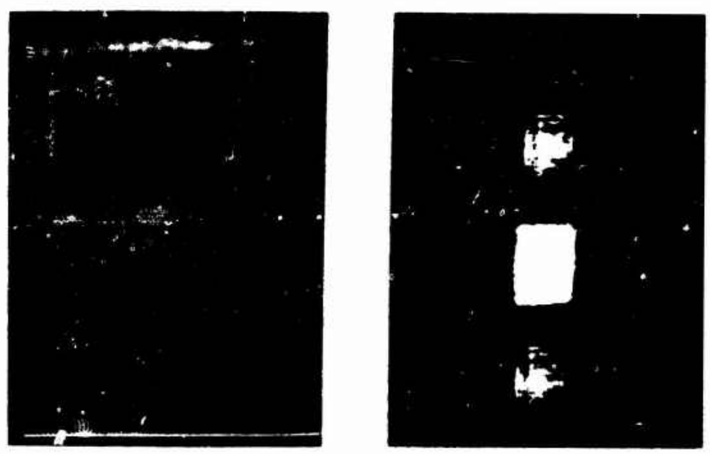
Simultaneous Scanning (Coincident Source and Receiver)

Aperture: 4.2 x 5.3 cm @ 32 1/cm

Frequency: 10 MHz

Figure 62. Comparison of Normal and Simultaneous Scanned Holograms

(TRANSDUCERS FIXED, OBJECT SCANNED)



Hologram

Reconstruction Image "Off Axis"

Aperature: 4.2 x 5.3 cm @ 32 1/cm

Frequency. 10 MHz

Object: 1.6 x 2.4 cm, 13 cm from Hologram and "On Axis" of Aperture

Figure 63. Plane Source-Point Receiver Simultaneous Scanned Hologram and Reconstruction

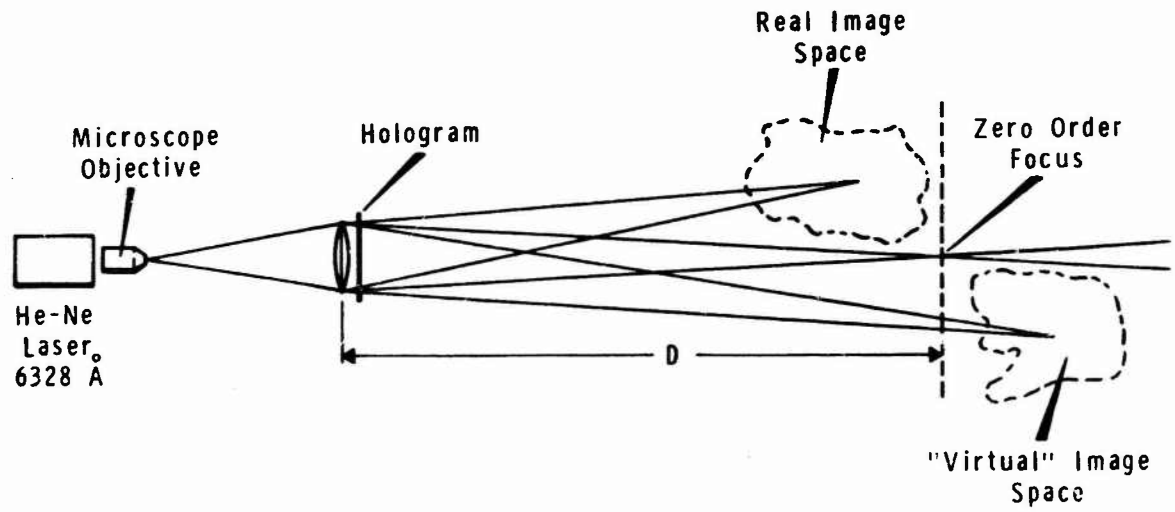


Figure 64. Acoustical Hologram Reconstruction Geometry

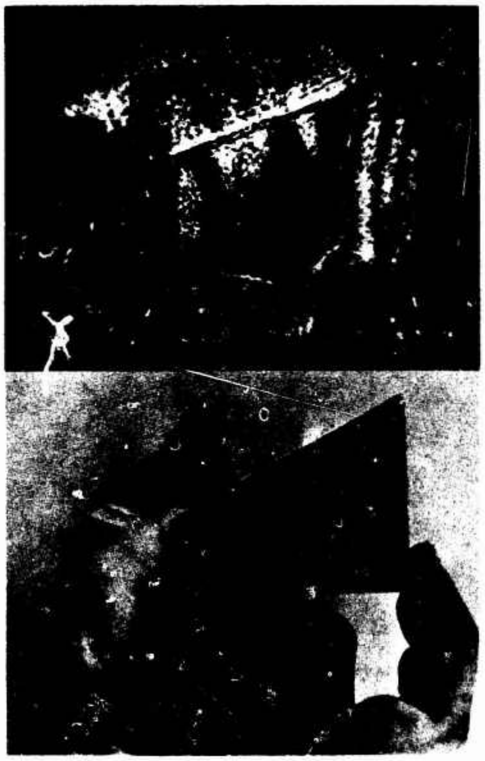
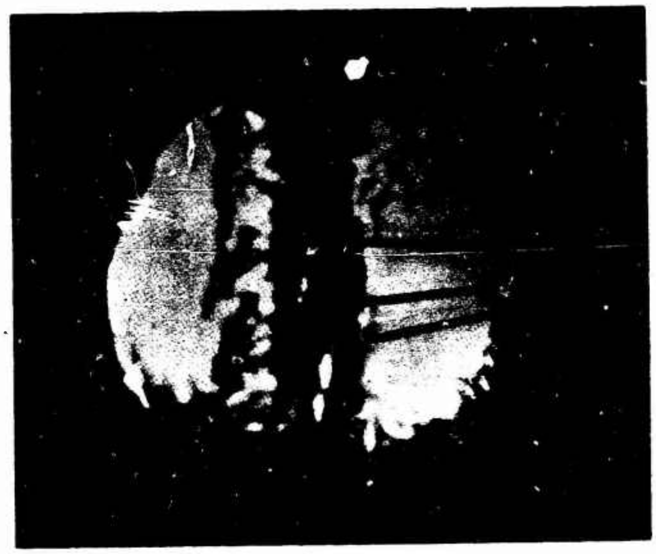


Figure 65. Acoustical HNDT-Brass Wedge with Drilled Holes

In photo at top, interior of quarter-inch thick brass wedge is shown as it appears on the viewing screen of liquid surface nondestructive inspection system using ultrasonic holography. The dark stripes reveal a pair of tenth-inch holes drilled into one edge of the brass, with one of them intersected by a single hole drilled into the opposite edge. Note operator's fingers holding sample in object tank. The bottom picture shows the plate in normal light.



MAJOR FLAWS

Figure 66. Acoustical HNDT Image of Flaws in 1/2-Inch Stainless Steel Butt Weld.
19-066-519/AMC-71

TYPICAL NON-DESTRUCTIVE TESTS

Examples of the non-destructive testing capabilities of the Ultrasonic Imager. The unit is equally effective with ceramics, nonbonds and composites.

REAL-TIME IMAGE

HONEYCOMB STRUCTURE

Imaged at 5 MHz.

Boron Epoxy	0.030"
Aluminum Honeycomb	0.50"
Fiberglass	0.040"

INTERNAL VOIDS IN PLASTICS

Photo shows high strength, high temperature plastic block.

Block is 0.400" thick.

REAL-TIME IMAGE

PLASTIC BLOCK

Smallest hole is 0.0145" in diameter, yet is clearly visible.

Imaged at 5MHz.

Figure 67. Other Examples of Acoustical HNDT

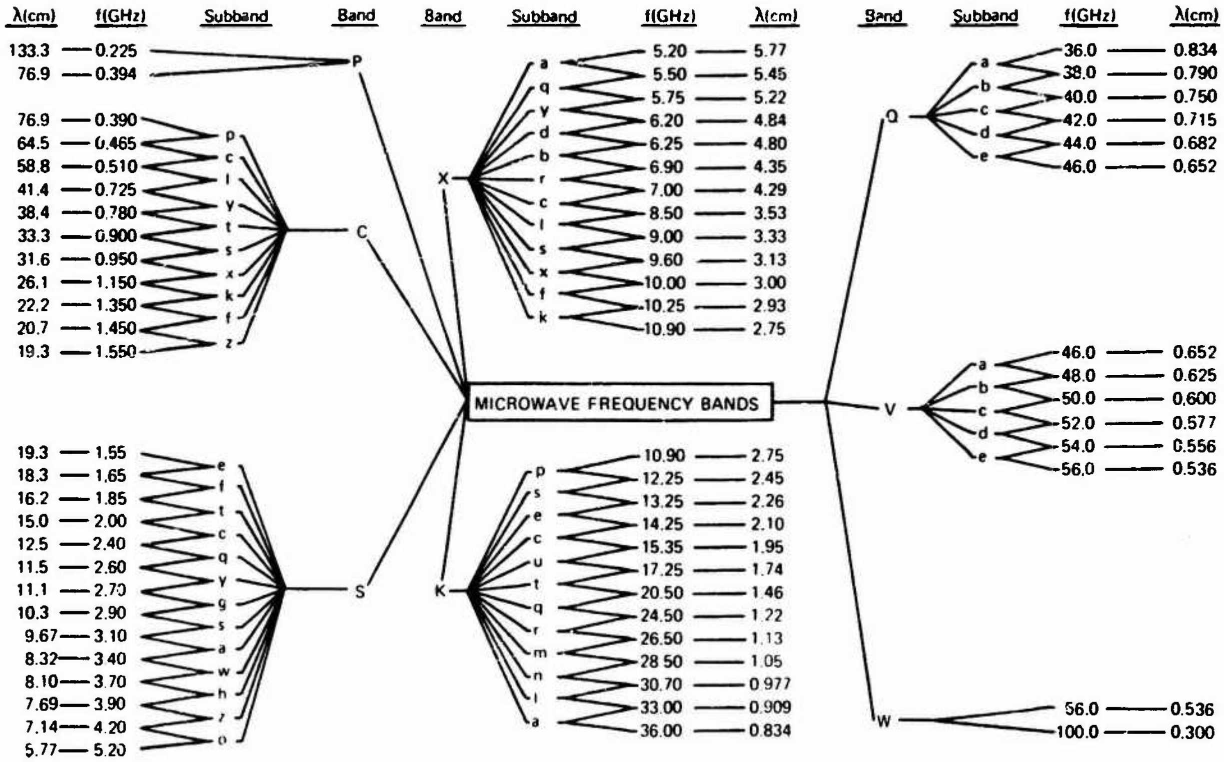


Figure 68. Microwave Frequency Bands[640]

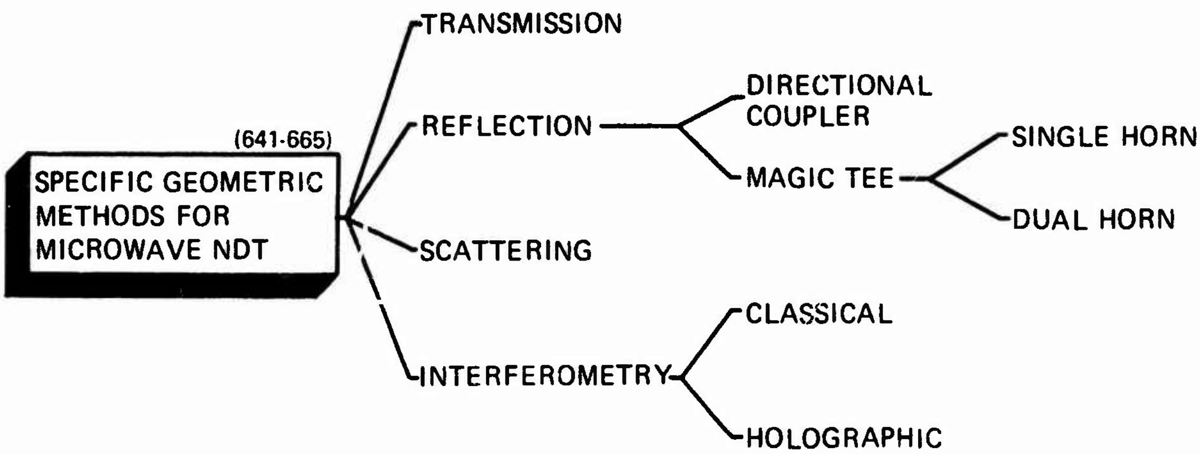


Figure 69. Specific Geometric Methods for Microwave Nondestructive Testing

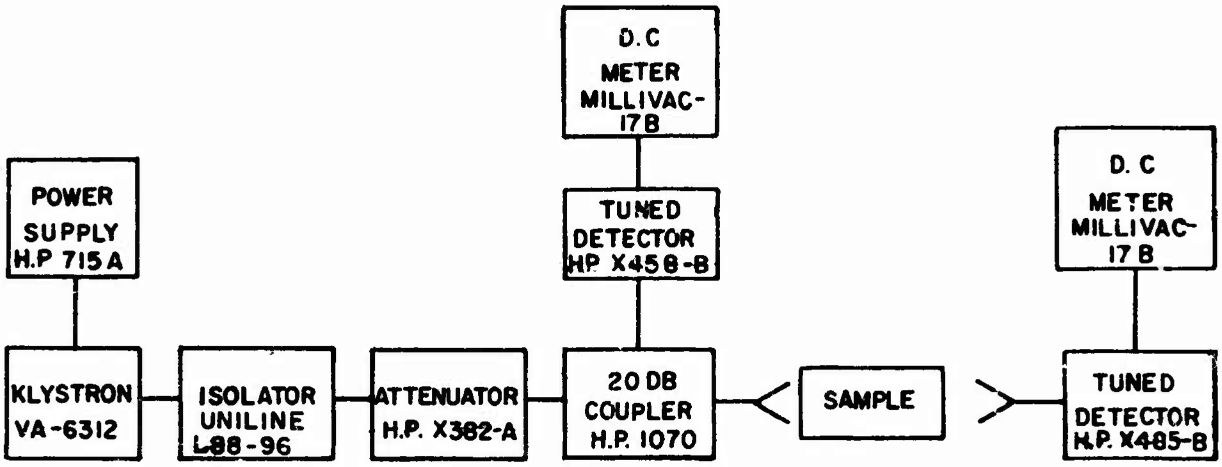
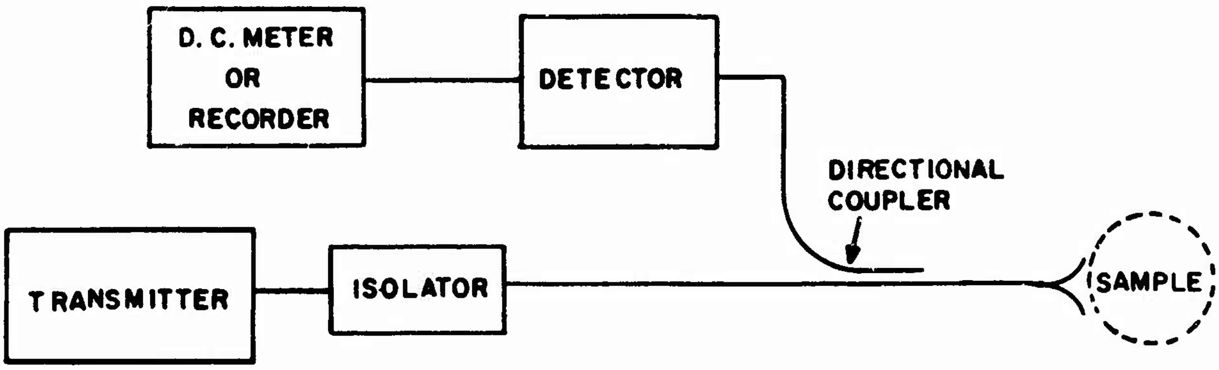


Figure 70. Block Diagram of Microwave Transmission Method



NOTE: BY REPLACING THE TRANSMITTER BY A SWEEP OSCILLATOR, SWEEP TECHNIQUE CAN BE USED

Figure 71. Microwave Directional Coupler Reflection Technique

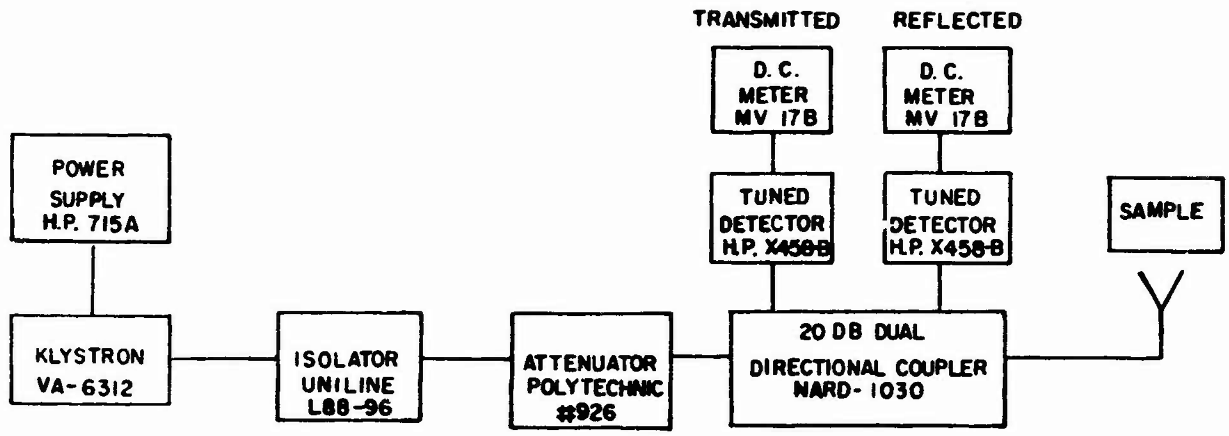


Figure 72. Block Diagram of Microwave Reflection Method

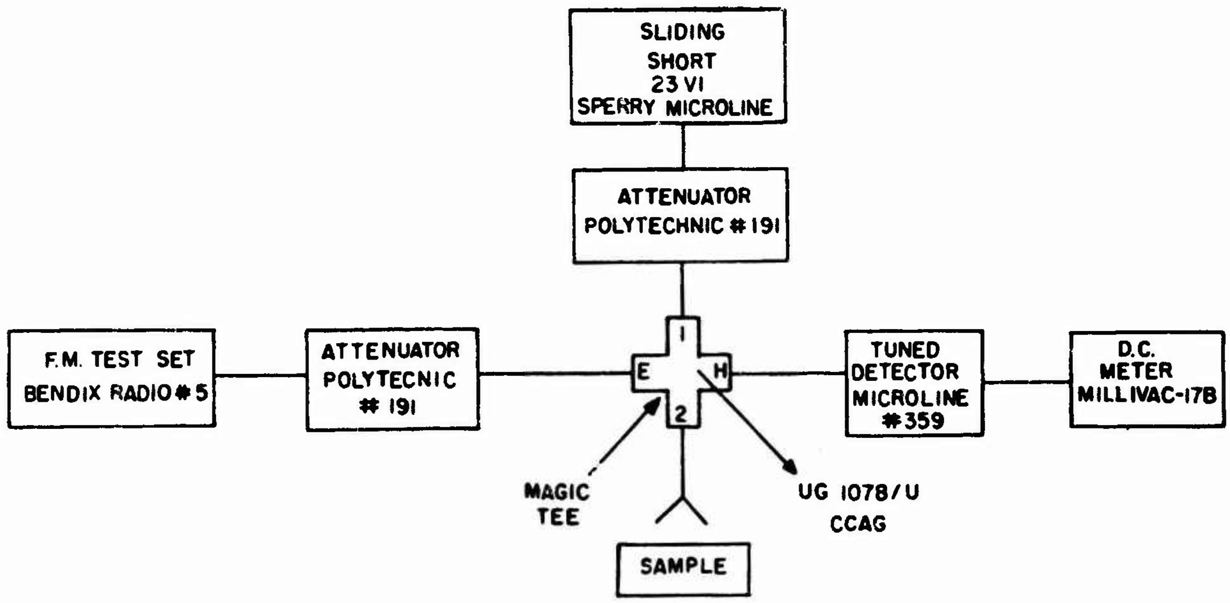


Figure 73. Block Diagram for Microwave "Magic Tee" Reflection Method

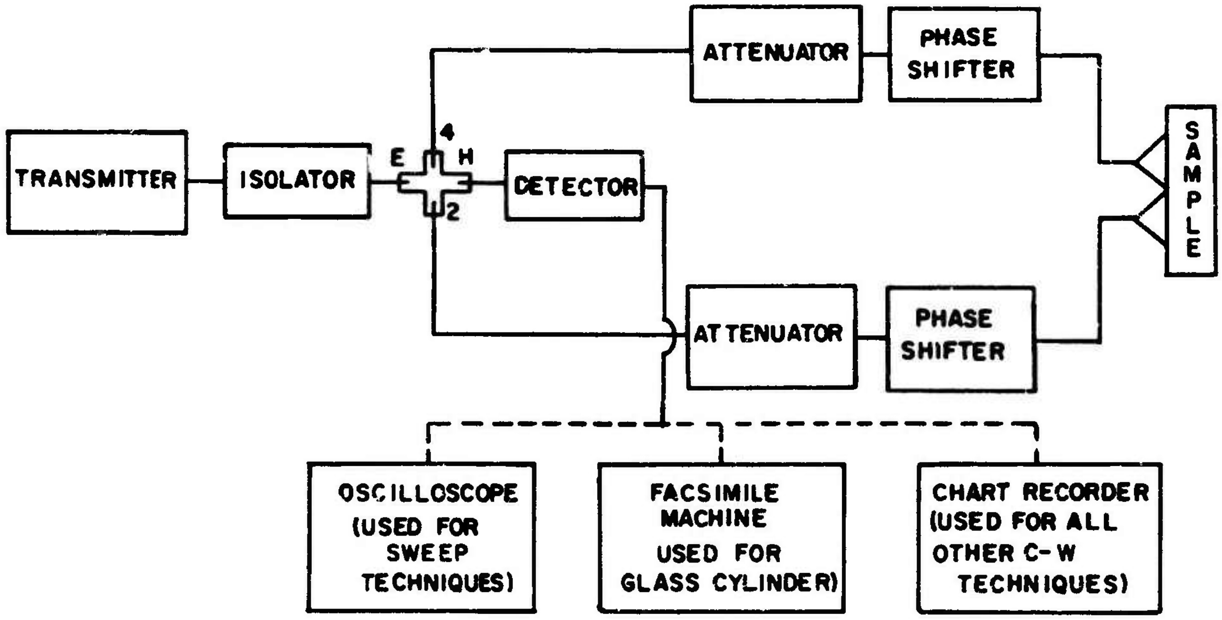


Figure 74. Microwave Dual Horn Technique

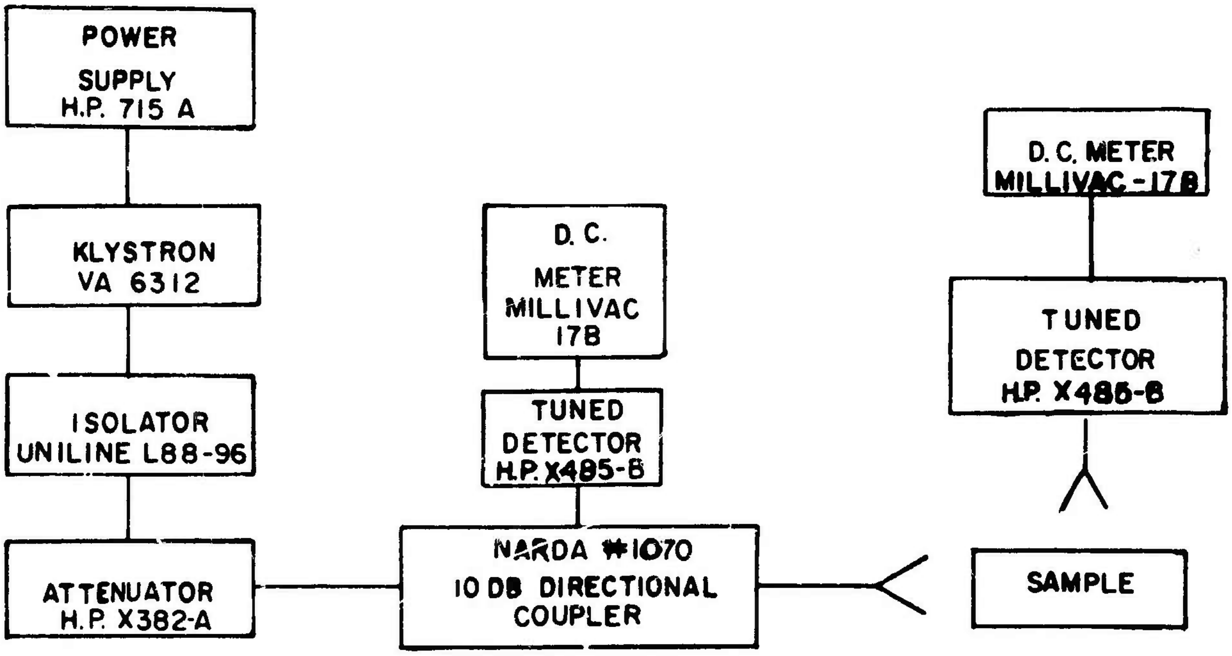


Figure 75. Block Diagram of Microwave Scattering Method

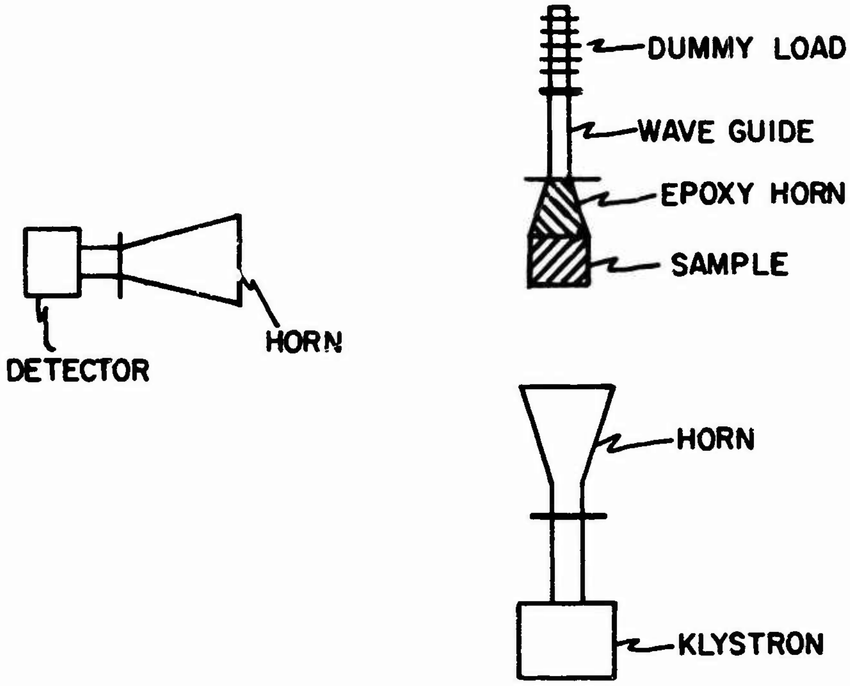


Figure 76. Microwave Scattering Arrangement

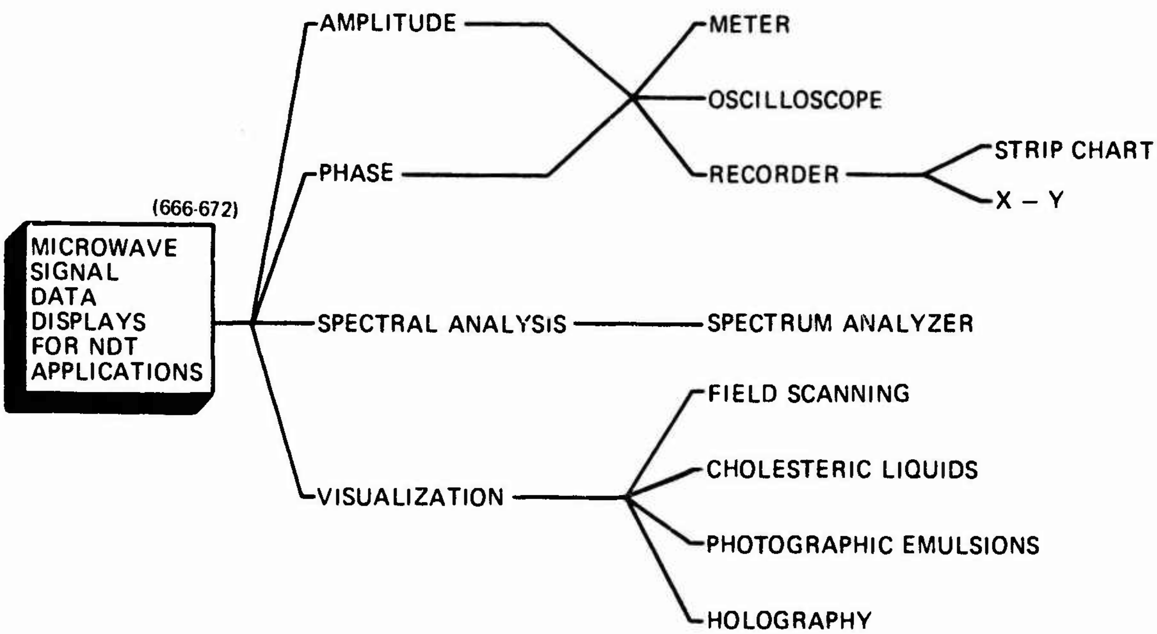


Figure 77. Microwave Signal Data Displays for Nondestructive Testing Applications

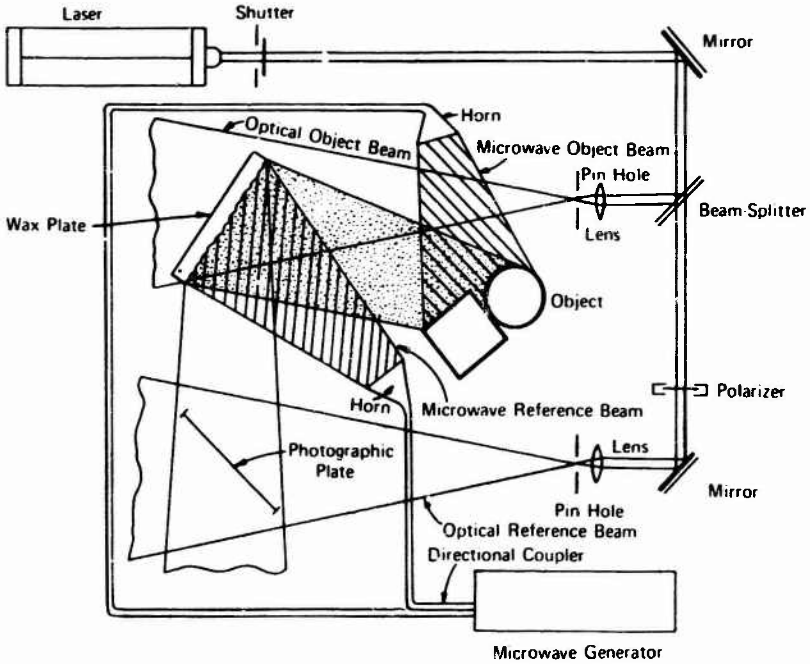


Figure 78. Microwave Hologram Construction and Reconstruction Processes

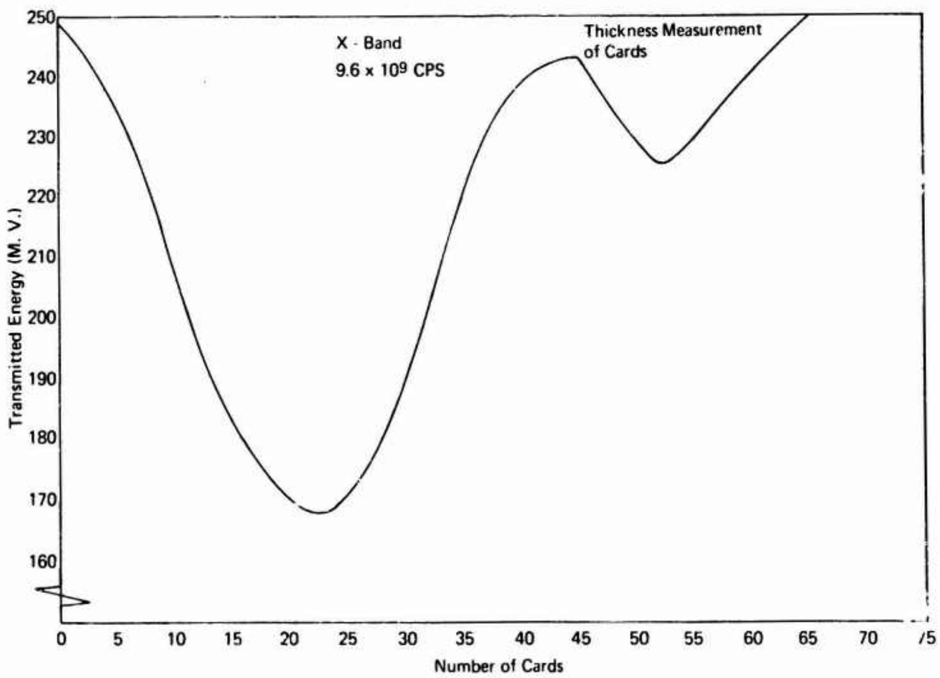


Figure 79. Calibration Curve for Transmitted Microwave Energy Versus Thickness of Plastic Cards

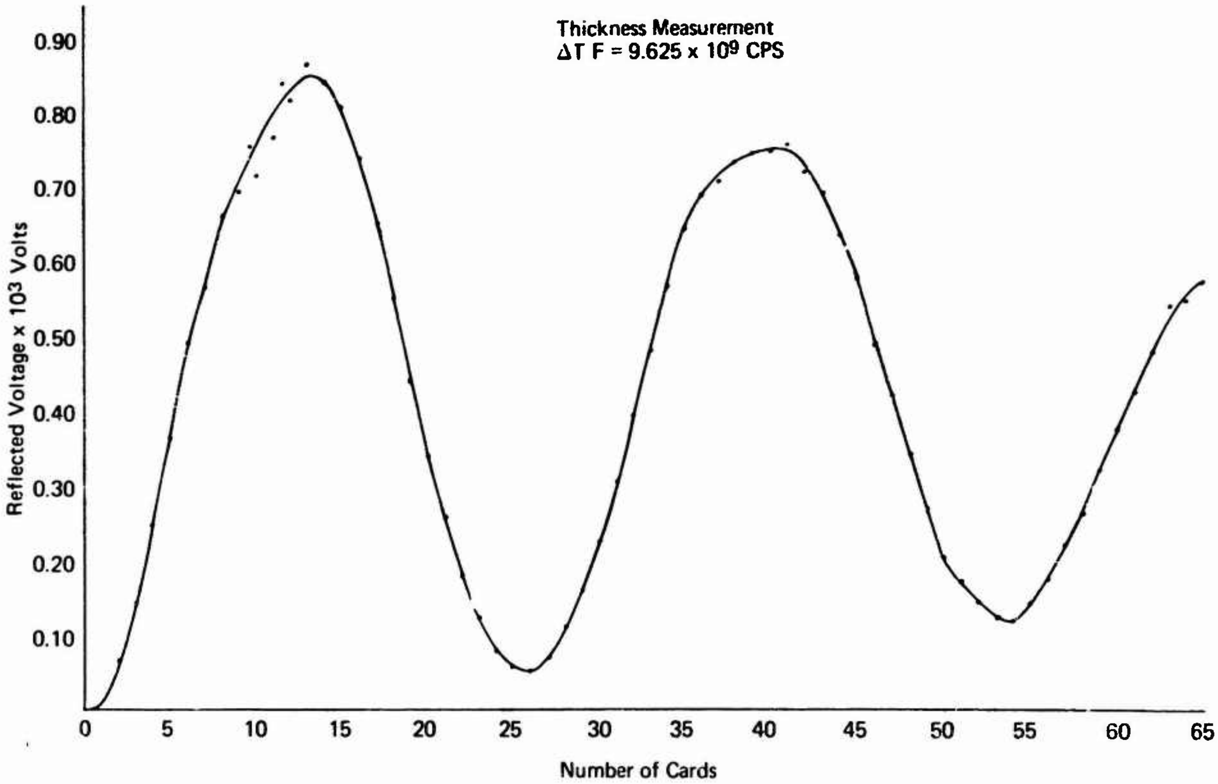


Figure 80. Calibration Curve for Reflected Microwave Energy Versus Thickness of Plastic Cards

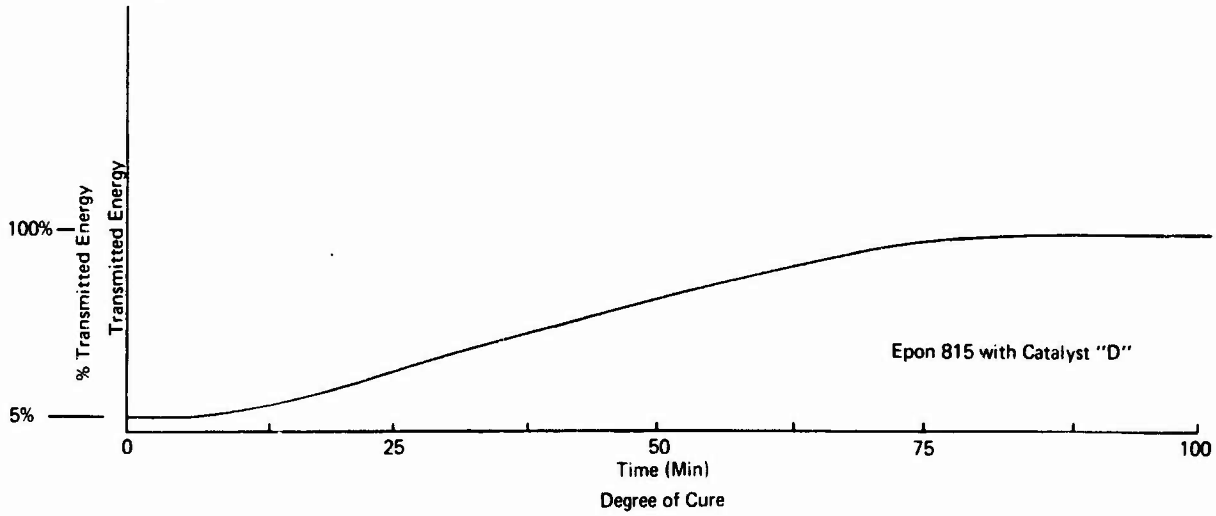


Figure 81. Curve of Transmitted Energy Versus Degree of Cure

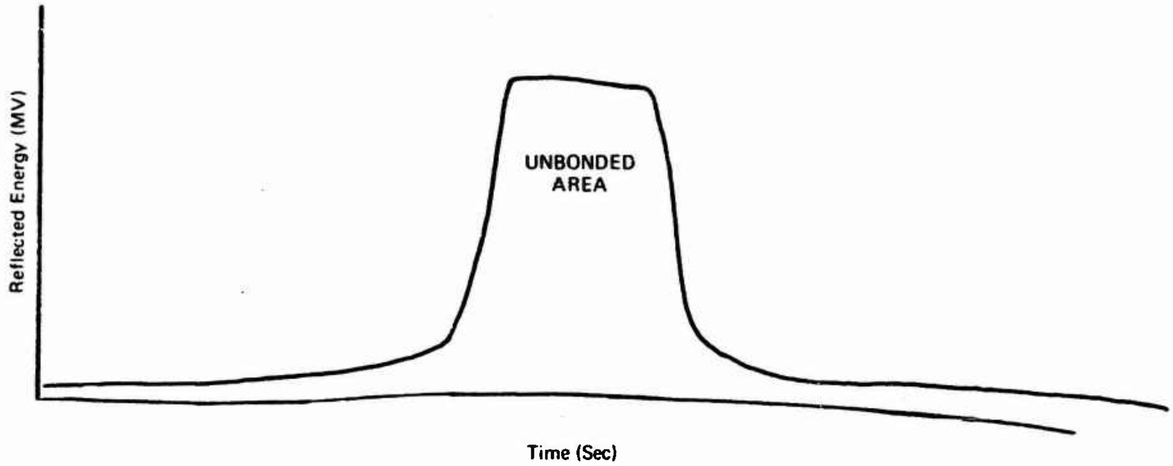
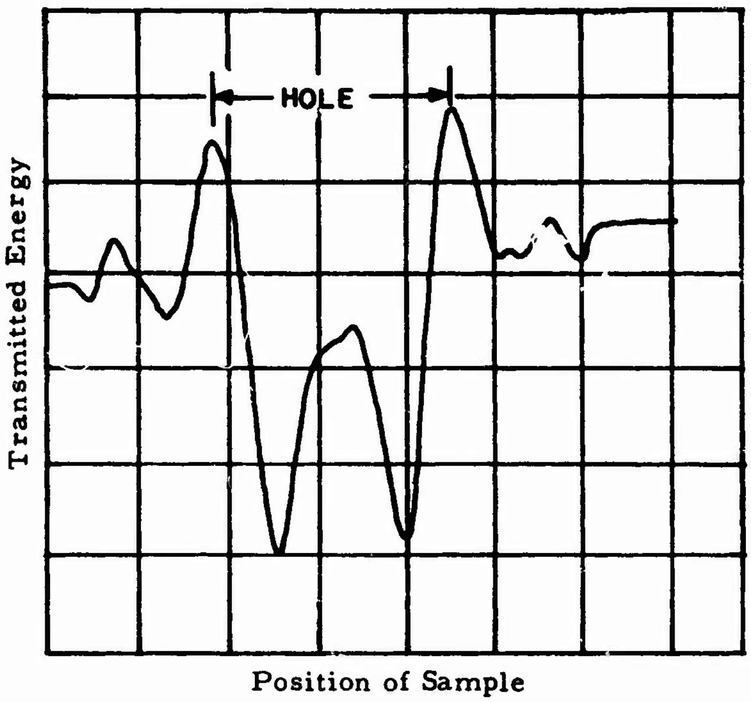


Figure 82. Microwave Scan of Filament-Wound Plastic Sample with Area of Unbond



NOTE: Microwave frequency was swept from 27.8 to 40 GHz at a rate of 100 sweeps/sec. The sample was scanned at the rate of 1 inch per 10 sec, so the values on the graph are averages for the frequency range.

Figure 83. Microwave Scan of Urethane Foam Sample Containing a 1/4-Inch Hole

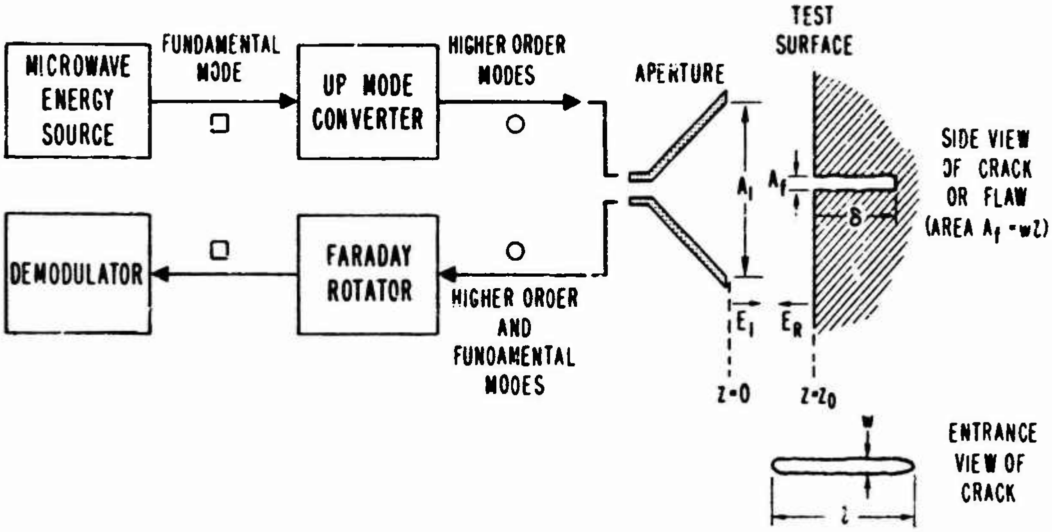


Figure 84. Schematic Diagram of Aperture and Crack Width Nomenclature

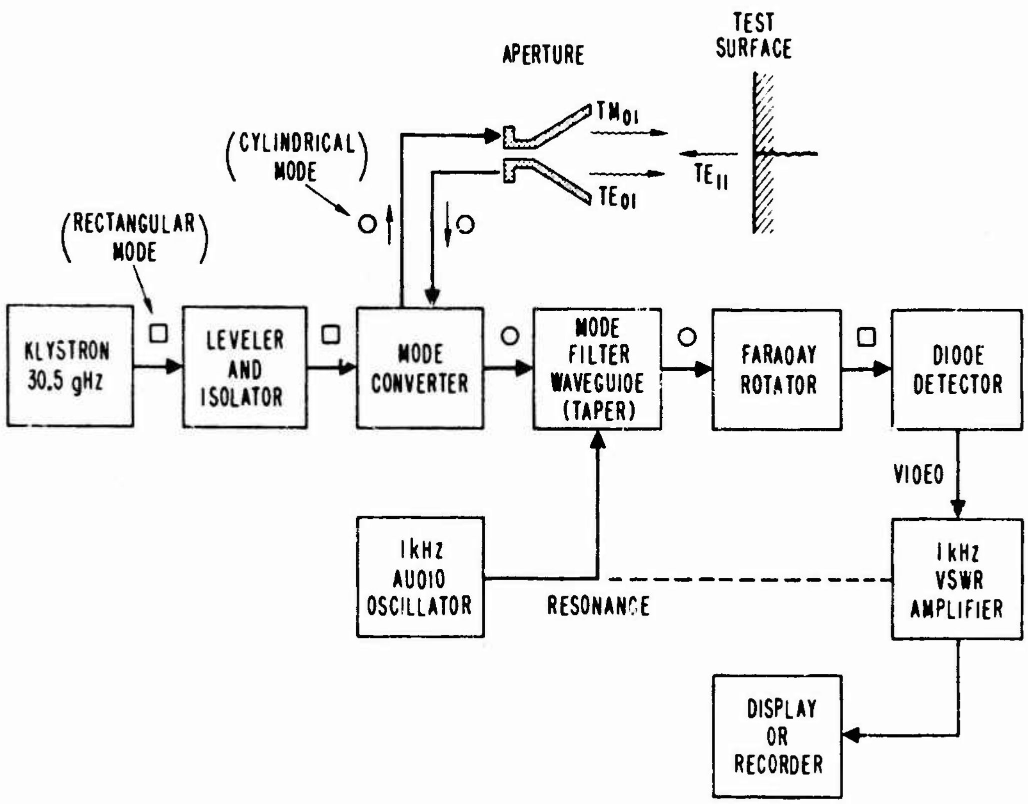


Figure 85. Microwave Slot-Depth Measuring System

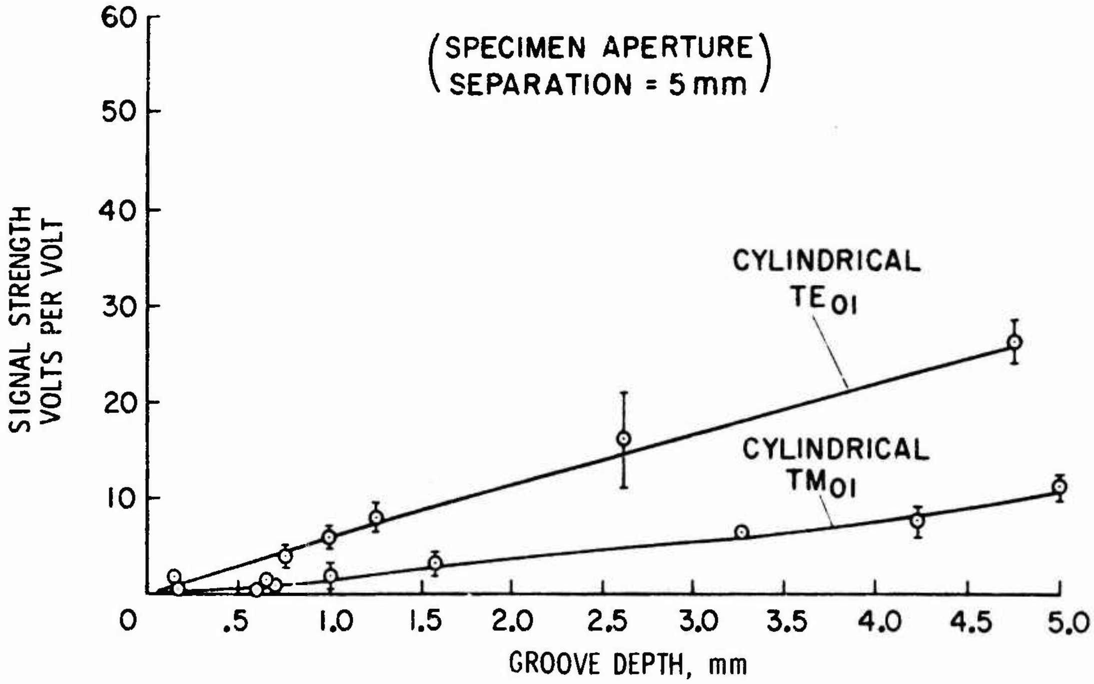


Figure 86. Signal Strength Versus Experimental Slot-Depth for Aluminum

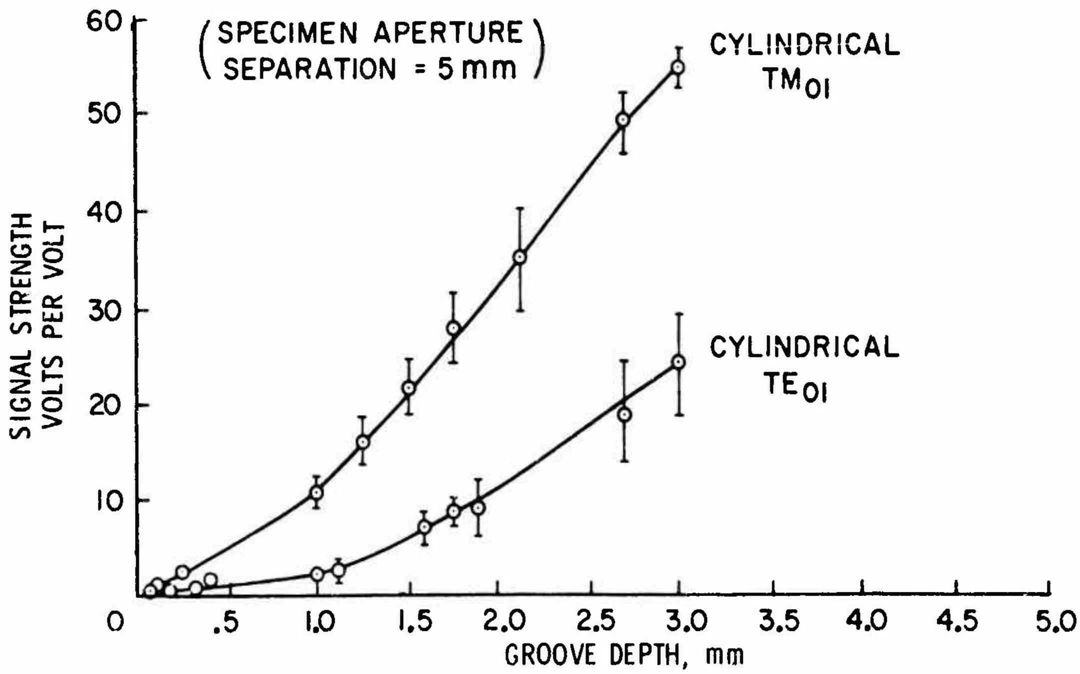


Figure 87. Signal Strength Versus Experimental Slot-Depth for Steel

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